SCIENTIST

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Robert S. Morison, M.D.

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Foreword

A CENTURY AGO, IN A SIMPLER AND SMALLER AMERICA, THE question of choosing a profession was, for a young man, no agonizing decision. In the first place, professions were relatively few—minister, lawyer, physician, teacher—there were not many more choices. Then, too, if a young man chose to go into business or journalism or farming, there was no problem about professional training, for there were no schools for such callings. Nor had the professions become subdivided. If a teacher in a college had an interest in science he might well be a professor of "Natural Philosophy" and never have to decide whether he was a chemist or a physicist, a geologist or a biologist, much less to choose between such fields as astrophysics and biophysics.

Today the situation is far different, and there can be no doubt that young people are having a harder and harder time making up their minds about their future careers. Parents tend to worry about this fact, and some of them have confessed to me growing concern because their sons had not reached firm vocational choices by the sophomore year in college. The concern is understandable, but it is ill founded, for, in general and with some limits, the later a young man arrives at his decision, the less apt he is to make a mistake. And a mistake may lead to a real waste of time, effort, and money.

There are a good many reasons why it is more difficult for young people to choose their vocations than it was fifty years ago. Society is infinitely more complex, and part of its complexity is reflected in a host of new professions and occupations and specialties, unknown and even undreamed of before the First World War. One has only to think of the airline traffic manager, the specialist in space medicine, the television repairman, the nuclear engineer, the computer programmer, the X-ray technician, the public-opinion analyst, to realize that the list of new callings could be extended almost indefinitely. To make matters worse, both the old professions and the new ones require more education and more specialized training than formerly. Not too long ago a young man with or without a high school diploma could become a lawyer after working a few years in a law office and taking the required examinations. Now admission to the bar is usually preceded by four years of college and three years of law school.

Still another factor making for an increase in the difficulty of vocational choice is the growing tendency to self-analysis among students. Today's students are heirs to some decades of spreading information and misinformation about psychiatry; victims of hundreds of mental tests, projective tests, and aptitude tests; beneficiaries of a deepening concern in school and at home about the problems of adjustment; and it is no wonder if they hesitate long and painfully before reaching conclusions as to their own abilities, motives, and goals.

Considering the problems in connection with career choices that all young men and women are facing, and realizing that what they needed most to help them was truly authentic information about the various professions and vocations, I came to believe that a series like this one would be most useful. Discussion with a number of edu-

cators and guidance counselors confirmed the idea, and The Macmillan Company welcomed it as an opportunity to be of real service to young people in secondary school and college.

The plan for this series calls for a limited number of books on the most important callings. Each is written by a person who has actually practiced and is intimately acquainted with the vocation in question, and who has achieved notable distinction in it. Each is designed to present in a thoroughly factual manner the problems of entrance into and practice of the different professions. But the volumes do more than that, we hope, for they are intended to give a vivid picture of what it is like to be a lawyer or a professor or an engineer or an architect. Moreover, they endeavor to convey a sense of the personal requirements, the rewards, and the sacrifices involved in the various vocations. There is no attempt at "salesmanship," no effort to romanticize the professions or to heighten their color. What these books are designed to do is to help young people in the most practicable way possible in one of the two most vital decisions of life (the other being marriage).

In this volume Dr. Robert S. Morison faces a most difficult task, for the profession of scientist has, in the last half-century, assumed a sudden and dramatic importance. Scientists sit at the right hand of presidents, generals, and businessmen in the making of the crucial decisions, and sometimes it is only the scientist who can understand the point at issue. Science has changed the world more in the last sixty years than it was changed by all forces in the previous six hundred. Scientists talk a language of their own and live in a realm where others cannot penetrate. It is no wonder that science has taken on an importance, a glamour, and an attraction so great that a young man or woman may decide to be a scientist without any adequate realization of the problems and the obligations involved.

Dr. Morison endeavors to face the situation squarely. He explains what science is and what it is not. He examines some difficult questions as to the validity of scientific knowledge and its relation to other kinds of knowledge. He does not, like so many other scientists, ignore the humanities and the social sciences, for he understands full well their importance to education and to civilization. He seeks ever to give a sense of what it is like to be a scientist and to think scientifically.

Born in 1906, Dr. Morison attended Phillips Exeter Academy and Harvard University. He received his A.B. degree at the latter in 1930 and his M.D. at Harvard Medical School five years later. After serving as a resident physician at the Collis P. Huntington Memorial Hospital in Boston, he taught anatomy and physiology at the Harvard Medical School for a decade before joining The Rockefeller Foundation. There he has risen to be Director of the program in Medical and Natural Sciences—a post of key importance that has brought him into close contact with scientists of every land, ranging from Nobel Prize winners to young students from the new countries of Asia and Africa.

Thus Dr. Morison is especially fitted to write about what it means and what it takes to be a scientist. More than most of his colleagues in the scientific world, he has a sense of the past and of the future as well as of the present. Like the best of them, he has a real humility, a respect for facts, and a faith in reason combined with a healthy skepticism. I would even hazard the guess that a young man or woman who is thrilled and captivated by this volume has a scientific type of mind and will make a good scientist.

CHARLES W. COLE

Santiago, Chile
April, 1963

Preface

FOR BETTER OR FOR WORSE THIS BOOK HAS TURNED OUT to be rather more personal in tone than I had expected or the publishers may have intended. It is, in effect, a statement of what I think is important about science and, therefore, about being a scientist. I have written as a person with scientific training and interests, though not always as a scientist. There are, as the reader will see, many expressions of opinion in the book. They are on the whole my own personal opinions and not necessarily those of all scientists, although I hope that most of the opinions would seem reasonably sound to most scientists.

The book has three major themes, and they are not always clearly separated from one another. They may be stated as follows: (1) What science is; (2) What it is like to be a scientist (and how one becomes one); (3) What science has to do with life in general. Generally speaking, the first four chapters deal with the first topic, chapters 5 through 11 with the second, and the last three chapters with the third, but there is a good deal of overlap among them.

Because one of the good ways of indicating what something is is to differentiate it from what it is not, I have taken a little time to describe other methods of knowledge in chapters 1 to 3, and in Chapter 5 to delineate certain differences between the scientist and the professional man who applies

science in his daily work. The fact that the first six chapters are largely devoted to drawing distinctions of this kind may make the book start too slowly for some readers. Such people might better plunge right in at Chapter 7, "How to Become a Scientist."

Nevertheless, I can't help hoping that a considerable number of readers will find it interesting to review some of the thinking that has been done over the years on the nature of knowledge. Only in this way can one really understand what it is that gives science its peculiar power and its almost equally surprising limitations. I am well aware that many, perhaps most, competent scientists care little about the philosophy of science, but I found it impossible to write a book about being a scientist without first trying to say a little bit about what science is.

The last three chapters are perhaps the most personal in the book and they deal with subjects which are viewed very differently by different people. The observations and opinions put forward here represent a very tentative and preliminary attempt to describe some of the relationships between science and other essential forms of human activity.

I suspect that at least the last chapter, "Science and Policy," will seem very remote to young people attempting to choose a career. I included it for at least four reasons. (1) It is important for everyone to recognize that science is involved intimately and continuously with decision-making of the greatest importance for our daily lives. (2) Anyone going into science may be involved in high policy discussions much sooner than he might suppose. (3) We are still in the process of working out a satisfactory relationship between science and the world of affairs, and it seems desirable to stimulate as many people as possible to start thinking about it as soon as possible. (4) The writing of this chapter gave me an opportunity to clarify my own thinking.

I hope that more young people may find some interest in the ideas sketched in chapters 12 and 13 about art and morals. I really do not have any special competence in these matters, but I am anxious that young people engaged in the reappraisal of value questions that has always characterized their time of life should not fall into the facile fallacy that science has nothing to do with the finer things or with eternal verities.

Finally, some of my colleagues have objected to Chapter 11, "Day of a Scientist," on the ground that it deals with a number of personal problems peculiar to adult life which are sure to seem unreal to people in their late teens or early twenties. There are two sorts of answers to this. The first, and most practical, is that the youngest of my colleagues, who typed the manuscript, liked it and thought it helped her to understand that scientists (and adults) are really people. The second, and more theoretical, answer is that since one is an adult for a much longer time than one is a teenager, it is wise to get as much data as one can before deciding what kind of adult one wants to be.

A number of people have helped me in writing this book, especially my brother Elting Morison, who looks at science with the eyes of an historian and *littérateur,* my wife, who thinks of scientists as people, and my friend Charles Frankel, who very kindly went over the philosophical parts to keep me from making too many naïve mistakes. (I did not take all his advice, so there are still some things that are probably wrong or imperfectly interpreted; he must not be blamed for them.)

Several patient and extremely skillful people helped to translate the manuscript into typescript from what my old algebra teacher used to call the "turkey tracks" in which it was originally set down. Miss Doris Neuer, Miss Barbara Post, and Mrs. Thomas Flagg deserve especially honorable

mention in this respect. Miss Mildred Runciman took complete charge of such matters as spelling and the accuracy of reference to other books. Where the punctuation and syntax follow established usage, she is also responsible. Improprieties indicate where she lost the argument.

ROBERT S. MORISON, M.D.

Peterborough, New Hampshire
November 29, 1963

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1

The Background of Modern Science

THIS IS PROBABLY THE FIRST CENTURY IN HISTORY IN which any appreciable number of young people can seriously say to themselves that they are considering science as a career. Science has of course existed for a much longer time, but until recently it has usually been practiced as a sort of side issue by priests, magicians, engineers, physicians, or gentlemen farmers. They drew their financial support from the art which they practiced and used their leisure or extra time to advance pure knowledge. The astronomer Kepler summed the situation up very well when he said that God who has given each animal a specialized means of support has given astrology to astronomy. Society is accustomed to pay people for doing only those things that seem to bring more or less immediate benefits, and the public at large has only now come to realize that it is worthwhile to pay people to develop organized knowledge about the nature of things.

A little later we will briefly review the development of science by earlier Western societies in order to put the problem in perspective and to understand what it is about modern science that makes it so different from what has gone before. But first let us take a look at how different it really

is. In the first place we have very much more scientific knowledge than any people has ever had before. It has been more or less reliably estimated that scientific knowledge has been doubling every ten years since about the middle of the eighteenth century. Unless one is used to dealing with geometric progression of this sort, it is hard to visualize exactly what this means. To illustrate how very nearly overwhelming it is, we may say that children growing up today have access to eight times as much knowledge as their fathers, 64 times as much as their grandfathers, and over 1,000 times as much as their great-grandfathers had.

The increase in the number of scientists and, as a corollary, the increase in the number of career opportunities have been even more abrupt and astonishing. Here the staggering statistic is that 90 percent of the scientists who have ever lived are alive today.

Furthermore, science is involved in almost every aspect of our lives. It is obvious to everyone that the telephone, radio, television, the automobile, the airplane, and the rocket are the direct results of modern science. It may take a moment longer to realize that the food we eat and the clothes we wear could not possibly be provided in the necessary amounts, nor could our people live closely together in cities, without the constant application of science. The contribution of science to health and survival is perhaps no better seen than in the following figures. In nonscientific societies a quarter to a half of all babies born are dead before one year has gone by. In a highly scientific society the figure is only 1½ percent.

Finally, modern science has greatly altered the way that man thinks about himself and the nature of his hopes and fears. Before the scientific era, man lived in constant fear of hunger, pain, and death. His food supply depended on the capricious acts of nature which were attributed to hos-

tile deities of various sorts. Great plagues could sweep down from nowhere and wipe out whole families and villages. Such dramatic manifestations of nature as thunder, lightning, and raging winds were not understood but could only be endured as reprisals from on high for man's wickedness.

Oddly enough, this abject impotence in the face of natural phenomena was frequently coupled with very inflated notions of man's place in the scheme of things. Man believed himself to be the most important being in the world and the world was clearly the most important part of the universe, situated quite obviously at its center! The gods might be capricious and often frankly hostile, but there was no doubt that they had a primary interest in man and spent a lot of time thinking about him.

Science has reversed this picture. In advanced societies it has almost completely removed the fear of hunger, pain, and premature death, or at least has reduced them to manageable proportions. Even when we cannot control the forces of nature—as in the case of the still unconquered diseases or the occasional ravages of hurricanes—we feel that we know a good deal about them. The paralysis of fear has given place to an energetic attack that must ultimately bring these, too, under control. While science has been conferring these powers and dignities upon man, it has also given him a much more humble picture of his place in nature. It is no longer obvious that man is the highest form of living things. Instead of inhabiting the center of the universe, he occupies a minor planet in a third- or fourth-rate solar system on the periphery of a not unusual galaxy. Even on earth his status is at best ambiguous. He has been here for a much shorter time than most other species and his future is by no means guaranteed. Although at the moment he occupies a rather conspicuous place in the order of living things, he is in no important sense above

that order but is intimately dependent upon it. His outstanding qualities of intellect are to be understood not as a share in the Divine Wisdom, but as the result of an evolutionary process that provides each and every species with some specialized means of survival. In other words, man has an unusually good brain for much the same reasons that a tiger has unusually good teeth and claws, or a cow has an unusually good apparatus for digesting grass.

Many species met disaster in the past when the conditions for which they had developed specialized abilities disappeared. Everyone knows, for example, what happened to the giant reptiles when the climate changed. Man has some advantage in that his form of specialization confers on him an unprecedented flexibility of adaptation. He can live under more different kinds of circumstances than perhaps any other species. But then too, his very flexibility and apparent freedom of choice may be his own undoing. For we now know that one of his choices concerns whether or not to press the button on the doomsday machine.

But let us turn now to our promised very brief review of the place of science in earlier Western societies. Among other things we may find that one of the factors which has determined the rate of scientific progress in different societies is the way they have regarded change in general and the relative weight they have given to improving man's control of natural forces as against preserving traditional images of man's place in the scheme of things.

A very good start in science was in fact made by the ancient civilizations in Egypt and the great valleys of the Tigris and Euphrates rivers. These highly organized societies depended primarily on the fertility of the bottom land they occupied and its annual renewal by the silt brought down in the spring floods. Since it rarely rained in these areas, the water necessary for agriculture had to be supplied

by irrigation. These basic facts and necessities early led to the development of methods for predicting the rise and fall of the rivers, and for constructing dams and canals. It was noticed quite early that the rise and fall of the rivers occurred when the sun and stars were in particular positions in the heavens. This observation led to a great interest in mapping the heavenly bodies and plotting the courses they pursued during the year. In order to do this accurately it was necessary, of course, to develop instruments for measuring angles and a method of noting down the observations. Much the same methods were useful in measuring and dividing the land. Arithmetic, geometry, and elementary trigonometry developed in this way, hand in hand with astronomy and surveying. Problems of irrigation led in the same way to elementary knowledge of certain physical principles underlying the art of engineering.

The success of these primitive sciences, coupled with the development of a highly organized legal and social system, made these societies far more productive than the hunting and grazing ones of the nomadic tribes which inhabited most of the world. Indeed the great river civilizations of the Middle and Far East were so successful that they existed for a far longer period of time than have any that succeeded them.

Stability and lack of change became prized beyond all other things, and it is probably this fact that kept science from developing as we know it. The essential astronomical and engineering knowledge became vested in the ruling priests who dictated the distribution of land, the time of planting and reaping, and the construction of dams and canals. Their position of power and privilege depended on their superior knowledge which they therefore preferred not to share with others. They also made little effort to increase knowledge since they had enough to maintain their society

the way it was, and they were bright enough to see that new knowledge might lead to a different kind of society that would be harder to control. For those who see some relationship between creativity in the arts and scientific creativity, it is interesting to note the conclusion of scholars that much the best and most original painting and sculpture was done during the early dynastic periods in these monolithic societies. Later on, art forms became conventionalized and repetitive much as did the scientific effort.

The Greeks had a very different kind of society and a very different attitude toward knowledge. Greek civilization was much less centralized and was much more interested in variety and individual achievement than were the great river civilizations. Agriculture was less highly organized, and trading with other parts of the world played a much greater role. All this resulted in a society that was more ready to change and much freer in thought than were the irrigation societies of the great river valleys.

The advancement of knowledge seems to have been less closely tied to developing the means of production and perhaps more concerned with determining man's place in nature and in answering the question, "What is the good life?" In this sense the Greeks were perhaps somewhat more devoted to "pure" science and somewhat less to its applied aspects than the people who came before or after them. Science was, in fact, closely related to philosophy and played an important role in the total effort made by the Greeks to understand and enjoy life in all its aspects.

Since the Greeks did so well in the development of mathematics and astronomy and made a good start in medicine and biology, it is difficult to understand why the world had to wait nearly 2,000 years for the development of science as we know it. Doubtless many factors were involved, but there is one to which I would like to call atten-

tion particularly, since it highlights what is perhaps the most important element in the method of modern science.

On the whole, the Greeks seem to have paid too much attention to the use of their heads and not enough to the use of their hands. They were captivated by the beauty of the mathematical methods they had developed and they made great progress in the use of language as an instrument of logical thought. So successful were they that they came to believe that the truth can be discovered and proved by reason alone. They were much less concerned than the modern scientist is in finding out whether their thoughts actually agreed with the way things are in the world we see and feel. As a result, they made relatively little progress in inventing instruments with which to extend the ability of the natural sense organs to observe the outside world, and they did practically nothing to develop an experimental method. The celebrated experiment Archimedes made in his bathtub to determine the specific gravity of the king's crown may be the exception that proves the rule.

The Greeks had a number of reasons for their attitude, some good and some not so good. In the first place, it is a fact that the results of good mathematical or logical reasoning often do agree precisely with observations in the natural world. We shall have more to say about this later on. It may also be noticed that much of the manual work in Greek society was carried out by slaves. The aristocratic citizens of the Greek city states tended therefore to look down on the mechanical arts which could have helped them in observing nature. This downgrading of manual work often leads to erroneous ideas about the nature of man and his destiny. In varying degrees, almost everyone believes that human beings consist of two parts —a material body with many embarrassing and objectionable characteristics, and a spiritual part which is beautiful,

reasonable, and in some sense immortal. There has always been a strong tendency to identify the spirit of man with the *real* nature of the universe. The material part both of man and of the universe is then given a secondary, accidental kind of role. The Greeks were a good deal less embarrassed by their bodies than most people, but nevertheless their philosophers were much more interested in ideas and reason than in material things. Plato, the greatest of them all, built his whole philosophy on the notion that ideas in the mind of God constitute the essential structure of the universe. To him and to many others who came after him, the material things we see and feel were but pale and imperfect shadows of this eternal order. This tendency to minimize the status of the material world tended in turn to keep intelligent men from looking at it very carefully. Most people thought it unlikely that one could get at the essential ideal structure or plan by studying its admittedly imperfect results. Instead they relied on the use of their reason, which was felt to be the most godlike of human qualities, to figure out what went on in the divine order.

A quite different group of people who also grew up in the Eastern Mediterranean, the Jews and their Christian descendants, were equally impressed by the difficulty of understanding the world by studying it directly. Incidentally, they had less reason to study the world from the practical point of view than the Egyptians and Babylonians did, since the Jews during their great period were primarily nomads and shepherds and depended relatively little on organized agriculture and industry. Like the Greeks they were primarily interested in getting a clear idea of the spiritual nature of man and his relationship to certain universal truths. They placed less reliance on reason than the Greeks but relied on God to reveal di-

rectly to them how the universe is ordered. Extraordinarily gifted people, with powerful imaginations and great literary skill, they put together the Book which served the Western world for nearly two thousand years as a principal source of beliefs about both the material and the spiritual worlds.

At the close of the ancient period these two traditions, the Greek and the Jewish, provided the basis for the development of the Christian church which dominated all the affairs of Western men from then on. By and large, the church, especially in its early period, took an even more skeptical view of the material world than either the Greeks or the Jews. Impressed by all the admittedly bad things that occur in the world of everyday experience, the greatest thinkers and the most holy men found virtue in renouncing this world and looking for salvation in the next. Knowledge of both worlds was sought through an incomparable development of the methods of revelation and right reason. The power and beauty of the method are probably no better seen than in the work of St. Thomas Aquinas, who succeeded magnificently in bringing Greek thought (especially that of Aristotle) and Jewish revelation together in an ordered system which explained almost all aspects of the material and the spiritual worlds. So orderly it was, and so satisfying to most people, that efforts to change it or even to call attention to any events which might not be in accord with it were often punished as heresy.

The medieval period is thus the most typical and thoroughgoing example of a time when man consciously endured a high degree of physical hardship and anxiety while preserving a stable and at the same time exalted picture of his relationship to God and the universe. No one should belittle either the motivation or the results of this way of life,

but it is, of course, as far away from modern science as one can get. Medieval society had many values which ours lacks and will have a very hard time reestablishing. One of the more delightful ways of acquainting oneself with these values is to read *Mont St. Michel and Chartres* by Henry Adams, who was incidentally a very modern Protestant as well as the first medieval scholar in the United States.

Toward the end of the fifteenth century, a number of things began to happen which turned thoughtful men's attention to the material world as an object of study. This is not the place for even a brief review of the changes that brought about the Renaissance and culminated in the Reformation and the so-called "enlightenment." Suffice it to say that they involved every aspect of society from art, which became much more naturalistic, to politics, which became more democratic and pluralistic. The principal point of interest to us is that these changes made it psychologically and, at least to a limited extent, legally possible to look at the world as it "really is" rather than merely to accept the carefully worked out statements of the medieval schoolmen.

As soon as this was done, it turned out that there were serious defects in the whole structure of the knowledge built up on the basis of reason and revelation. Perhaps the first big break was the discovery by Copernicus that one could make a much neater, more beautiful picture of the solar system by regarding the sun rather than the earth as its center.

Galileo struck much more violently at the old system when he found a way to describe motion in terms of a single set of principles. Hitherto, motion had been thought of as a property of individual objects so that, in principle at least, there were as many different sorts of motion as there were objects. Actually this idea is not so absurd as

it sounds when put in this extreme way. It grew out of the everyday observation that light objects like pillows or feathers fall rather slowly, while heavy ones like stones or cannon balls fall fast. Aristotle built this idea into his system of explanation which relied heavily on the idea that objects have a series of intrinsic properties and purposes which largely determine their behavior.

What Galileo essentially did was to show that it was much easier to understand motion if one looked at it as something imparted to an object by outside forces. He never quite said it in these words, but his whole line of thinking and experimenting led in this direction and paved the way for Newton's very clear statement of the case later on. By conducting his experiments in such a way that forces attributable to friction and air resistance could be neglected, he was able to show that, in fact, all bodies accelerate at equal rates when rolling down an inclined plane or falling freely. Later investigators invented the air pump and confirmed these views by repeating the experiments in a vacuum so as to eliminate air resistance completely. In summary then, Galileo, by a combination of rare insight and uncommon ability to design what we now call controlled experiments, was able to demonstrate the basic principles of motion. These principles made it easy to describe the behavior of any object in terms of outside forces acting upon it, and paved the way for what is now rather loosely called the mechanistic way of looking at the universe in general.

Galileo's work had far-reaching effects. In the first place, it turned the attention of thoughtful men to the importance of checking the results of reason and revelation by an appeal to the observed facts under carefully controlled conditions. In the second place, it reopened discussion of what we mean when we say we have explained something.

Aristotle had tried to explain his erroneous views on the speed of falling bodies by saying that it was part of the essential nature of heavy bodies to fall faster than light ones. In the same way he explained the development of an acorn into an oak by saying it was the nature of an acorn to do just that. In fact, he went somewhat further than this and said that the oak was in some sense the cause of the growth and development of the acorn. He carried this form of reasoning into every aspect of human affairs. In a particularly celebrated case, for example, he not only explained but defended slavery on the grounds that it is part of the essential nature of some men to serve others.

As is well known, the church found it difficult to accept the explanation of motion offered by Galileo and he was subject to a series of investigations by the church authorities. The worries that motivated these investigations were similar in character to the worries that underlie the investigations carried out by our own Committee on Un-American Activities. On the whole, the threat to the medieval system of thought was more profound than are most of the matters that worry our current inquisitors. Nevertheless, the investigations seem to have been carried out in a more thoughtful and considerate manner than those that have so marred our own reputation for intellectual freedom. However that may be, the difficulty in which Galileo found himself with the Pope was only in part the result of differences of opinion about the speed of falling bodies and whether or not the earth moves around the sun. The really dangerous thing about Galileo was the way his experimental approach called into question the whole method of explanation worked out by Aristotle and elaborated by the church fathers into what is known as the Natural Law.

This basic difference in approach underlies many of the discussions and outright conflicts that characterized

the development of Western civilization from the time of Galileo to the present. Both points of view have, in fact, contributed importantly to our thoughts on many subjects. At the present time it appears to most of us that the point of view represented by Galileo has had rather the best of the argument when it comes to explaining the behavior of inanimate nature and the physical and chemical aspects of life. Nevertheless, the deep conviction of those who follow the Natural Law that there is an order to nature has also played a crucial role in the development of science as well as of social and political life in the West. The modern scientist may differ a good bit from Aristotle and St. Thomas as to the best ways of discovering, describing, and explaining this order, but he is equally convinced that such an order exists.

2

Why Do We Believe What Science Says?

We started the last chapter with the assertion that this is probably the first time in history when an appreciable number of young people can seriously say to themselves that they are considering science as a career. We turned aside for a bit to discuss some of the reasons why science has been relatively slow in developing and to sketch some of the other methods for understanding the world with which science has had to compete.

We must now take a more positive approach and ask what it is that has brought science to its present established position in civilized society. The reason that large numbers of students can allow themselves to think about going into science is that society is willing to provide them with laboratory facilities and salaries to live on. In 1962, for example, the United States was devoting approximately 8.1 billion dollars [1] to the support of science. Why is this so? Although one might think of several reasons, the overwhelming fact is that science has been successful in describing the nature of things in such a way that the resulting knowledge is useful in making life more comfortable and healthy for everybody and for defending ourselves from people who have different views from ours

on certain important matters. It is true that a few sophisticated people also derive pleasure and satisfaction merely from contemplating the kind of knowledge science provides, but their number is not yet large enough to account for the extraordinary public acceptance of science.

The interesting thing is that there is no better or more certain justification for the validity of the so-called scientific method than its manifest success. Nobody has ever succeeded in demonstrating that scientific knowledge is any closer to "absolute truth" than is any other kind of knowledge. In much of its work science makes use of the same sort of mathematical and logical methods that the Babylonians and Greeks did. Its logic is, in fact, rather less refined than that of the medieval schoolmen. From time to time science also uses human intuition in a way not very different from that of the mystics who developed revealed religion. The philosophical or metaphysical foundations of modern science are no more and no less sound than those of the more traditional means by which man has sought to explain himself and his place in nature.

What then are the secrets of its success? Many scholars have tried to find the explanation in a description of something called the scientific method. It turns out that it is extremely difficult to describe the scientific method if one thinks of that term as describing a single set of well organized procedures which, properly followed, will inevitably turn out the right answer.

I myself like to think of science as organized childishness. This statement is, of course, not a complete definition but it highlights several important points. If we follow a young child around for a while we notice that he moves about rather rapidly, looking at things, taking them in his hands, turning them over and over to get a better look, throwing them on the floor to see if they will break, put-

ting them in his mouth to see how they taste, and so on. Slowly the child begins to have expectations about the objects he handles. Things that are clear and easy to see through are likely to break when they fall on the floor. Things that make one feel warm as we approach them are likely to feel painful when actually touched. Very hard things don't have much taste, whereas most soft warm things do. None of these ideas or generalizations is completely satisfactory because each is likely to have a number of exceptions. About the only one that works out every time is the statement that all objects which are pushed off tables fall to the floor. In order to develop more accurate expectations about the world of objects, the child keeps on exploring and refining his description of objects and their relationships to one another until he finally emerges with a satisfactory working picture of the world around him.

There is really no difference in what the scientist and the child do. The only difference is in the skill with which they do it. The scientist is just as interested in looking at the world, listening to it, feeling it, and tasting it as the child is. And he does these things for just the same reason —to improve his expectation as to what objects will be like and how they will behave when he encounters them again. He differs from the child in having learned to doubt the accuracy of his own senses and by wanting to see, feel, and hear more than his unaided senses can supply. He therefore spends a lot of time devising instruments with which to observe the world and to reduce the qualitative impressions of his senses to numbers on a scale. He has found, for example, that people disagree rather easily about how red an object is but have much less difficulty if the redness is described as a certain wavelength and is measured by a pointer on a dial. Another advantage in

describing the world in terms of numbers is that it makes it possible to describe relationships between objects in terms of mathematical formulas. Although many young people find numbers rather frightening and difficult to learn, the fact of the matter is that the language of mathematics is the easiest and most convenient way of describing certain kinds of relationships.

One of the most famous examples of the power of mathematics to give a neat and convenient way of describing relationships is the work of Sir Isaac Newton in formulating the laws of motion. Galileo had provided many of the original observations on which Newton's work was based. The kinds of questions they were interested in answering ran somewhat as follows: How far will a bullet go when it is fired from a cannon? How long will it take a stone to reach the earth when dropped from a given height? Why does the earth go around the sun faster than the planets which are farther away? Is there some overall relationship between these different types of events? Newton found that there was such a basic relationship and stated it as follows: $F = Ma$. This is a simple way of saying, "All objects, no matter what their size or shape or what they are made of, tend to move at increasing speeds if you push steadily on them. The rate at which they accelerate is directly proportional to the strength of the push and inversely proportional to something I am going to call the mass of the object." (I shall have something more to say about the last phrase in this sentence in a later chapter. It is more significant than it looks.)

It is important to notice that the equation was designed to take care of all objects acted on by any forces and at all speeds. This is what we mean when we say that science is interested in making general statements about the world. In its essence, the process is the same as that

followed by the child who comes to the conclusion that all objects fall to the ground when they are pushed off tables. Good scientific generalizations are more general than this; that is, they say something about how the object will move if we throw it as well as if we merely drop it. They also describe the result in more precise quantitative terms—how long it will take to reach the ground, for example.

It should be said as soon as possible that scientific generalizations are no more true in any absolute sense than the conclusions reached by the child. To explain what we mean by this, we can notice that sooner or later most children will encounter an instance in which an object released from the hand will go up instead of down. He will then have to modify his statement about all objects and make room for very light round objects called balloons. In exactly the same way, the scientific world after 250 years of complete confidence in Newton's "laws" found that they did not account for certain events involving very small particles and very high speeds. It was Einstein, of course, who provided the equations to deal with such instances.

The spectacular progress of science between the sixteenth and nineteenth centuries had tended to make men feel that at last a method had been found which could bring us to an understanding of ultimate truth. The Einsteinian revolution was a great shock and caused a number of scientists and philosophers to reexamine the logical foundations of science. The discussion is a difficult one to follow and we will mention only the conclusion and a few of the high points here. The conclusion essentially is that science has no way of being absolutely sure that what it says is "true." About the best that can be said is that we believe scientific statements because they work

and because they give reasonably simple and often quite beautiful formulations of the relationships between objects or events. One of the reasons they work so well is, paradoxically enough, that we are now always prepared to find out that they don't work. We are sure of our result only when we use a scientific generalization to predict events which past experience tells us are likely to come out right. If we push beyond this familiar area we are more than ready to note any departures from our expectations and revise our generalization so as to take these new events into account.

Scientists as a group, therefore, differ from most other adults in being much more interested in what they don't know than in what they do know. Indeed, it is only by constantly testing what they think they already know that they can be at all sure that they really know it. It is this constant testing of both old and new ideas about how the world is put together that characterizes science and sets it apart from almost all other human endeavors.

The modern point of view toward the validity of scientific statements has several important corollaries. In the first place, it means that science cannot become interested in statements that cannot be tested by seeing whether they fit events which can be observed in what we call the "outside world." Questions which cannot be tested in this way are frequently referred to as pseudoquestions. Many important theological questions are of this character. No satisfactory test of the idea of personal immortality, for example, has ever been devised. Questions in the realm of esthetics encounter the same sort of problem. No one has ever devised a scale for measuring the beauty of a picture. About the best that could be done is to poll a large number of people and find that a certain percentage prefer the "Mona Lisa" to Raphael's "Dresden Madonna,"

but this is more a statement about people than about painting. We shall have more to say about some possible relationships between science and value problems in a later chapter.

A more surprising corollary of the nature of science as currently understood is that it has relatively little, perhaps nothing at all, to say about cause and effect. Indeed, science has progressed faster and become more useful the less it has paid attention to ideas about cause and effect.

The force of this perhaps surprising statement is best seen when we consider Aristotle's idea of final cause. It will be recalled that Aristotle felt that in some sense the oak tree was the cause of the acorn's growth and development. This concept rather obviously involves the additional idea that what we ordinarily call a purpose can also be a cause. The notion has a certain sort of explanatory value and is still used today in certain circumstances which do not call for a high degree of intellectual rigor. If a child asks why he has to eat, we tell him that he should do so in order to become a healthy man. We may even tell him that he has hands so he can put food into his mouth and a stomach so he can digest his food. In some cultures and in some periods of history, the very existence of domestic animals has been explained in the same way—for the purpose of contributing to man's welfare. All this seems so natural that it is extremely difficult to say what is wrong with it. I shall not even attempt to demonstrate in any logical way that the use of final causes or purposes as an explanatory device is wrong. Such discussions can easily be found in most standard works of philosophy, but they are not easy to understand. I shall merely content myself with asserting that science made much more rapid progress after it abandoned any consideration of purpose or final cause. There are several

reasons which might be advanced to explain why scientists gave up thinking in such terms but I shall mention only two. These two reasons are quite closely related to each other and may in fact boil down to the same reason. In the first place, if we answer a question in terms of purpose, we tend to shut off further questions; in point of fact, this is just why we do it. When the child says, "Mother, why do I have a hand?" and the mother replies, "In order to put food into your mouth, button your clothes, and so forth," the child usually says "Oh," and goes on about his business. Clearly Mother has saved herself an enormous amount of effort when she might otherwise have had to go into a discussion of how hands developed over millions of years of evolution. Aristotle saved himself perhaps a thousand years of work on the mechanism of growth and differentiation when he contented himself with saying that the oak is the cause of the acorn's development. But it is just exactly the willingness to undertake to describe growth and development in terms of preexisting rather than future events that leads to scientific progress.

The first reason, then, for abandoning final cause as an explanation is that it provides answers which are too satisfactory. The sense of satisfaction produced shuts off rather than stimulates further inquiry.

The second reason is really another somewhat more profound aspect of the first. The fact is that no one has ever figured out a way to submit a final cause to experimental test. How, for example, are we going to find out whether the oak is the cause of the growth of the acorn? We might think of cutting down all the oaks in the world and seeing if acorns still sprouted and differentiated into oaks, but we would immediately abandon the plan for two reasons. In the first place, it would be very expensive and probably illegal to do the job. Even if we could, however,

the experiment wouldn't be conclusive, since Aristotle and his colleagues would reply that it is not any particular oak but only the idea of an oak which is really the final cause. The idea of an oak is outside the reach of experimental techniques so there is no point in thinking about it from the scientist's point of view. Like immortality and the relative beauty of pictures, the idea of final cause has become a pseudoquestion.

Most people who speak of cause and effect are not thinking of final causes but of what Aristotle classified as primary causes. A classical example is found in the effect on billiard ball B when it is struck by billiard ball A. Surely science is concerned with this kind of cause, isn't it? The answer to this question is not nearly so clear as you might expect. What science in effect does is to assemble information about the past and present and use this to predict the future. Obviously this procedure involves some assumptions about how the past is related to the future. These assumptions, in turn, are much closer to the idea of primary cause than to the final causes discussed above.

Nevertheless, it has been known for a long time that it is at least very difficult and probably impossible to be absolutely sure that one event causes another. The usual attempt to discover such a relation is based on observing event A and noting that it is followed by event B. The seventeenth-century French scientist and philosopher, Descartes, employed a homely example to suggest that there might be something wrong about this procedure. He pointed out that it would not be difficult to arrange two clocks in such a way that one always struck the hour just a little before the other one did. If we observed this phenomenon for several days, it would be natural to expect in the future to hear clock B strike soon after we heard clock A. It would be almost as natural to say that the striking of

clock A caused the striking of clock B. It is obvious that our first expectation would be more or less correct if nothing happened to disturb the original arrangement, but our conclusion about cause would be quite wrong. Philosopher David Hume, writing at about the time of the American Revolution, explored the problem very thoroughly and came to the general conclusion that there is no way of being absolutely sure that one event causes another or that any amount of knowledge of the past can give us certain knowledge of the future. We do not have the time or space to explore his interesting discussion any further in this book. Those who have the inclination to do so can easily read the original in Hume's *Treatise of Human Nature* or the condensed account given by Bertrand Russell in his *History of Western Philosophy*. Incidentally, David Hume, besides being the most courageous of philosophers, is also among the easiest and pleasantest to read—even though his conclusions are bound to be upsetting to those who would still like to believe something with certainty.

After reviewing all the arguments he could think of, Hume states his final conclusion in his clear, earthy fashion, "The supposition that the future resembles the past is not founded on arguments of any kind, but is derived entirely from habit."

In actual practice, scientists worry very little about the questions we have been concerned with in the last few paragraphs and which are known in learned circles as the metaphysical foundations of science. They do, in fact, rely entirely on habit and they are quite content to do so because it works.

Most good scientific papers these days rarely, if ever, mention such words as "cause" and "effect" but the authors merely content themselves with describing what they

did and what happened next. Since their ultimate purpose is to arrive at some picture or theory of how events are put together, they may then go on to show that what happened is consistent with one idea and inconsistent with other competing theories.

For example, at about the time of the Spanish-American War there were two competing theories about the transmission of yellow fever from one person to another. One school of thought held that it was carried directly from one person to another through particles in the air derived from the bodily excretions of the sick person. Another school of thought held that the infection was carried by a mosquito that sucked up blood from one person and injected it into another during the process of biting.

The Army doctor, Walter Reed, arranged with several courageous volunteers to settle the matter in the following way. One group was asked to live in a room furnished with beds and bedding stained by the excretions of yellow-fever patients but protected from mosquitoes. The other group lived in a clean room but were exposed to the bites of mosquitoes that had fed on yellow-fever patients. All the people in the first room stayed well, while several of those in the second room fell ill. The evidence was consistent with the mosquito theory but inconsistent with the older one. Immediately it became clear that one way of controlling epidemics of this very dangerous disease was to keep down the mosquito population. A campaign was undertaken to do just this and yellow fever was in a very few years eliminated as a serious public health problem.

Much scientific work is of this same general character. It turns out that it is not really necessary or actually very sensible to ask whether mosquitoes are the cause of yellow fever. What we are really after is an accurate description of the circumstances in which yellow fever has occurred

in the past so that we can modify them in such a way that it is unlikely to occur in the future. Further studies have shown, for example, that the mosquitoes transmit a virus from one person to another, that the virus circulates in the blood of the sick person for a certain number of days, and that the mosquito must bite during that time in order to pick up the virus. Furthermore, only certain types of mosquitoes can carry the virus. The most important one happens to live in and about houses and to breed in rain-water which collects in household vessels of various sorts. The existence of yellow fever, therefore, depends on an intricate pattern of rain, tin cans, the presence of large numbers of nonimmune individuals living close enough together so the mosquitoes can fly easily from one to another, the presence of the virus, and so on. It is the knowledge of this entire chain of events that we really need in order to control the disease, and it is naïve to talk about one or another of the steps in the chain as *The Cause*.

It is important to note also that we really don't have to worry very much about the fact that there is some degree of uncertainty about each step. It must be admitted that most people do suffer from the urge to be absolutely sure about things or at least about some things. Skeptical people like Hume, who have repeatedly pointed out that it is impossible to be absolutely sure about anything, have never been very popular. Hume, of course, allowed that the fact that the sun has come up over the horizon every morning for several million years makes it very likely that it will come up tomorrow morning. Since his time science has made great progress in analyzing and refining the meaning of the phrase "very likely." These studies have been gathered together in a body of knowledge known as the theory of probability, which enables us to state the likelihood or probability of future events in terms of num-

bers. Modern probability theory seems to have been started by a lively and intelligent Italian physician * who spent much of his time gambling. In an effort to improve his returns, he invented methods for calculating the odds in various popular card and dice games, and the development of probability theory has been closely related to gambling ever since. A very sophisticated modern branch of such studies is actually named "Monte Carlo theory."

We cannot go into all the details of probability theory in this book. Suffice it to say for our purposes that it is now customary to express the probability that something will happen on a scale which extends from zero to one. Something that never happens is said to have a probability of zero. Something that always happens has a probability of 1. Something that happens half the time, like a penny coming down heads, has a probability of 0.5. Strictly speaking, the two ends of the scale are regarded as limits and, since we can't be absolutely sure about anything, it is customary to say that the probability of an event like the rising of the sun is very close to 1, or of the occurrence of a yellow fever epidemic in New York is very close to zero. Much more use is made of the intermediate parts of the scale; for example, the probability that a baby born in the city of New York will die before the end of one year is approximately 0.027.

One of the major uses of probability theory is to tell a given scientist and the colleagues he wishes to communicate with how sure he is that he is right. There are two kinds of problems here. The first is the relatively simple matter of asking how sure we are that some elementary

* Gerolamo Cardano (1501–1576). Because Cardano's work was not published until much later and exerted relatively little influence, credit is more usually given to a French nobleman, Chevalier de Méré, and the philosopher and mathematician, Pascal. Cf. *Lady Luck* by Warren Weaver, Doubleday & Company, Inc., Garden City, 1963.

measurement is "correct." The second is the more complicated matter of determining whether a relationship we have observed is a "real" relationship or only the result of "chance."

We shall discuss these two cases separately. It may come as a shock to many people, but it has been well known to scientists for a long time that it is impossible to measure anything absolutely accurately. There is always a margin of error. The errors may be of several different sorts but some possibility of error is always there. What the scientist does, therefore, is to make several measurements, average them up, and give a figure for the probability that anyone who makes the same measurements will get the same average result. (Actually the procedure is somewhat more complicated than this and there are several ways of stating the probability of error, but the point is that the scientist recognizes the probability that he is wrong and makes this numerically clear to everybody else.)

The second use of probability theory is much more important and interesting, for it bears directly on the problem of how we know that what we have observed about the past has anything to do with the future. So long as science was concerned with things that seemed to happen every time something else happened, as in the motion of billiard balls, Hume's worries about the theory of knowledge were of interest to theorists and philosophers, but they didn't bother practical men. Nowadays, however, science is increasingly interested in relationships which are much more complicated and involve so many variables that it is difficult to arrange things so that the same result occurs every time. The following example may help to make clear how such situations are handled.

A given form of pneumonia is known to have a case fatality rate which varies between 5 and 20 percent. We

have in our hands a new drug which is said to be helpful in reducing the mortality rate. Since very few drugs cure all patients and many patients get well anyway, how can we be sure that the drug helps? What we do is to set up two different groups of patients, say 50 in each, selected alternately as the patients come into the hospital. The drug is given to one group but not to the other. Ten patients die in the "control" group and eight in the one that received the drug. Offhand it looks as though the drug has a slightly favorable effect. At this point we ask ourselves what the probability is that the reduction in deaths occurred by chance. In other words, how likely is it that the reduction could be accounted for as the result of the normal variation in the severity of the disease and of unidentified differences in the way the two groups were selected? Our equations tell us that indeed the difference can be explained in this way and that the drug is in all probability ineffective.

If only three people died in the treated group, our calculation shows that this could have happened only 4 in 100 times as a result of chance so the odds are 96 to 4 that the drug "really works." The probabilities that different scientists find convincing vary somewhat but it is now fairly standard practice to "believe in" a relationship that might have been due to chance as often as 5 times out of 100.

The converse of this proposition is that most scientists are fully prepared to tolerate the probability that what they learn about the past will in one case out of 20 be a poor guide to what will happen in the future.

I am only too clearly aware that this discussion of the roots of scientific knowledge is not easy to follow and may strike many readers as irrelevant and boring. It seemed to me necessary to provide at least a skeleton outline, however, since there is still much misunderstanding about

what scientific knowledge is and how it can be used. Such misunderstandings are very significantly involved in public discussion of problems of great importance. The nature of these difficulties becomes much clearer if we consider a currently unsettled problem like the relationship between lung cancer and smoking rather than a long-agreed-upon matter like the infective cycle of yellow fever.

At the present time the lung cancer problem stands about as follows. The observed incidence of lung cancer in Europe and the United States has risen very substantially since 1920. The per capita consumption of cigarettes in the United States has risen in the same period from 1.89 lbs. per year to 9.61 lbs.[2] (1 lb. = 339 cigarettes) Males have the disease about 6 times as often as females.[3] During the 1920's and 1930's many more males than females smoked cigarettes excessively and there is still a considerable excess of male over female smokers. Coincident with the increase in female smoking, there has been a rise in female lung cancer. Further, if we ask 1,000 male patients with lung cancer how much they smoke we find that only five have never smoked at all and that 250 smoke more than 25 cigarettes a day. In a group of 1,000 men of the same age, weight, and social status who do not have cancer, 45 have never smoked and only 134 smoke as much as two packages per day.[4] Finally, if we gather together as many people as we can who have never smoked or smoked very little and match them against a group of people of similar age who have smoked a lot, we find that the death rate from lung cancer is 13 per 100,000 and 127 per 100,000—in the two groups respectively.[5]

You would think offhand that this evidence would be enough to convince the public and their representatives that smoking cigarettes is a serious public health problem and that something should perhaps be done to reduce the

number of cigarettes in just the way something was done to control rats when they were found to carry the plague or mosquitoes when they were found to be associated with malaria and yellow fever. As a matter of fact, a move has been made in England to control cigarette advertising, but as yet no such definite moves have been made in the United States.

There are, of course, a lot of arguments against doing anything about it: people enjoy smoking and may be willing to trade the pleasure for a significant increase in mortality; many farmers and the economy of whole states depend on the raising of tobacco; widows and orphans depend on the income from tobacco stocks; and so on. What interests us here are the "scientific" arguments. Some scientists have tended to dismiss the evidence just reviewed as "only statistical" and argue that it hasn't demonstrated that cigarettes are the cause of cancer. The difficulty with these two statements, both of which are perfectly true, is that they could equally well be directed against a great deal of scientific knowledge which we confidently employ every day. The best evidence we have that penicillin prevents people from dying is "only statistical." Indeed, the evidence wouldn't be much good if statistics had not been used. In an even more profound sense, our knowledge of certain important events inside the atom is "only statistical," and there now seems to be no possibility of getting any other kind. Furthermore, any number of public health measures have proved useful before scientists have identified the cause of the disease in question, and we have already seen that the notion of cause and effect is somewhat of a chimera anyhow.

What the opponents of the cigarette theory are really saying (and they have every right to say it and to be taken seriously) is something like the following: "You have not

yet convinced us that you have shown that cigarette smoking and lung cancer are related in such a way that the incidence of the disease will significantly decline if people abstain from smoking in the future. We remain unconvinced because there is still a reasonable possibility that the kind of relationship your statistics have demonstrated can be explained on the basis of coincidence such as that represented by Descartes's two clocks." More simply stated, the result may be attributable to the fact that the same type of person who gets cancer is the same kind of person who smokes a lot and that the two tendencies are related to some common factor in the person's constitution.

Fortunately there are ways of attacking this problem and efforts are already being made to identify constitutional or personality factors in smokers and nonsmokers and in cancer and noncancer patients to see how they line up. There is an even more convincing experiment that might but probably won't be done. All the teen-agers in this generation might find the evidence so far collected quite persuasive and abstain from taking up the habit. Thirty years from now the lung cancer rate might or might not return to somewhere near what it was in the 1920's and we would have our answer. Incidentally, I feel that the weight of the evidence is on the side of those who think that if teenagers decided not to smoke, there would ultimately be a substantial reduction of not only cancer of the lung but many other troubles of the heart and lungs which now shorten the lives of thousands of our citizens.

The situation surrounding the tobacco hypothesis, or the fluoridation of water for the protection of children's teeth is no different from that involved in the acceptance of any scientific theory except that there is more public discussion involved. There is usually no clear moment in time when a new hypothesis is agreed upon and an older

one rejected. Some scientists become convinced rather early and others will hold out for a long time. Much excellent scientific work is, as a matter of fact, undertaken primarily to convince the doubters that a proposed hypothesis is the best available.

Finally, a stage is reached when most scientists whose views count for anything agree on the point at issue, and attention moves to other problems. But in the back of everyone's mind is the possibility that new evidence will come up, sometimes by accident, which will throw the agreed-upon hypothesis into uncertainty and perhaps suggest a new one.

No average time can be given either for the general acceptance of a theory or the duration of its life once it is accepted. These things vary enormously. For the most part, however, agreement among all the people who matter occurs much more rapidly and completely in science than it does in other fields. This tendency to agree stems in large part from two factors: 1) Science confines itself almost entirely to the world as it is and not as it ought to be; 2) science has made tremendous efforts to reduce what it is talking about to "pointer readings" which, as we mentioned earlier, are much easier to agree about than are other types of descriptive statements.

Notes

[1] *Bulletin of the Atomic Scientists,* V. 17, No. 3, 29, 1962.

[2] *Statistical Abstract of the United States, 1961,* p. 802.

[3] Statistics provided by the American Cancer Society.

[4] *British Medical Journal,* V. 2, 1285, 1952.

[5] Royal College of Physicians, *Smoking and Health,* New York, Pitman, p. 19, 1962.

3

How Science Works

THERE ARE MANY DIFFERENT KINDS OF SCIENTISTS BUT only one kind of science. All scientists are engaged in the same enterprise, the description of natural events in terms of other natural events. The phenomena of day and night are described in terms of the earth's rotation on its own axis, the change of seasons in terms of the earth's movement around the sun. The heat of the sun, and therefore the heat of midsummer, is described in terms of the atomic conversions inside the sun. The plants that grow in the summer heat are shown to exist by converting the light of the sun into chemical links between the carbon, hydrogen, and oxygen atoms they absorb from air and water. The animals that eat the plants unlock the energy of these linkages to fuel the engines of their muscular apparatus and develop the electrical events in the nervous system that form the very patterns of thought itself.

This picture of the universe which has emerged with ever-increasing rapidity during the last five hundred years can be seen as a unity, but it is composed like a painting by Pieter Breughel of an almost infinite number of parts. The typical scientist proceeds by looking very intensely at a very small part of the universe. In the beginning he does his best to ignore the big picture since he has learned that if he looks at more than a very few things at once

he simply gets confused. Much of science began merely as an attempt to describe the physical world as it stands. It was perfectly natural to set about such descriptions one bit at a time. An obvious next step was to pull things apart and describe the constituent parts. Physics passed its simple descriptive phase some time ago; chemistry still devotes considerable effort to describing new compounds in terms of color, weight, form, melting point, and so on. Biology enjoyed a very long and important descriptive phase, partly because of the very richness of the world of living things. There simply are a great many things to dissect and describe.

The next stage was to describe changes in a single thing or in a group of things over time. For example, the early astronomers noticed at once that the stars changed their positions during the night and from night to night during the year in a regular way while the planets followed much more complex paths. Such motions could be noted and set down one at a time and later put together on charts and in mathematical formulas to provide some idea of how the solar system works.

Somewhat later, science began to encounter situations in which it was not nearly so obvious how to go about observing the bits and pieces in isolation from one another. The attempt to break down relatively complex systems into appropriate constituents for purposes of observation led to the development of the so-called controlled experiment. Although examples of controlled observation can be found in ancient and medieval times, the great development of the method may reasonably be said to have begun with Galileo. More than any other single factor, it is responsible for the remarkable development of modern science in the last four centuries.

To illustrate what we mean by the controlled experi-

ment as a method for observing the bits and pieces of complex situations in a meaningful way, let us begin by noticing some potatoes sprouting in a corner of the cellar. Most of them seem to be bending in one direction, and if we look in that direction we notice that the sprouts are pointing toward an open cellar window. We ask ourselves if there is any relationship between the open window and the direction in which the sprouts are growing. What shall we do to find out? First, let's put a piece of plywood over the window so that it becomes as much like the rest of the wall as possible. After a few days the sprouts lose their relationship to the window and seem to be growing straight up. Next, we ask ourselves what it is about the open window that seems to attract the sprouts. Three possibilities suggest themselves. Maybe the fresh air coming through the window is important, maybe it is the heat, and finally it could be the light. How shall we separate these effects from one another? We decide to begin by putting a glass sash in the empty window frame to cut off the fresh air but leave the light and a good part of the radiant heat. Again we come back in a few days to find that the sprouts are pointing toward the window just as they were before. Just to make sure that the fresh air might not have the same effect, however, we better think of some way of cutting off the light and arranging for the fresh air to come in. After a bit of fussing around, we arrange some cardboard boxes outside the window in such a way that air can flow through while the light is cut off. Now the potato sprouts grow straight up. We conclude that the fresh air is not important but that either the light or the heat rays (or both) are important. Now we have the problem of separating these two variables from each other. This can be done with suitable filters and if we can lay our hands on enough different filters

and an apparatus for measuring light intensity, we can come up with some pretty good figures on how much light of exactly what wavelength is necessary to produce a given amount of change in direction of the potato sprouts. From there we can go on to analyze the production of green material in the tips of the sprouts in relation to the amount of light of a given wavelength. As we proceed, we will find that the process of plant growth depends on the way the green material absorbs the light and uses it to combine the carbon dioxide (CO_2) in the air with water to produce carbohydrate. The speed of the process depends in part on the amount of CO_2 and water available and in part on the temperature, the availability of nitrogen, phosphorus, potassium, and several other elements. The effect of each one of these factors can be analyzed by separating it out in much the same way we separated the possible effect of the fresh air from the effect of the light.

Often it is not possible to remove a factor as completely as we removed the light or the fresh air. In such cases we content ourselves with holding this factor constant. For example, in the first part of our experiment we managed to hold temperature essentially constant by doing the experiment in a cellar. In technical terms we were "controlling" for the effect of temperature. Much of the time and effort of scientists goes into designing methods for controlling the effects of variables like temperature, pressure, and acidity, so as to observe the isolated effects of the particular variable in which they are interested.

Another procedure for isolating certain important elements from complex situations is almost purely intellectual in nature. It is known as abstraction and depends upon what seems like the simple ability to see what the members of a set of things have in common with one another. Until recently much scientific work in biology was devoted to

grouping living things on the basis of common properties. For example, birds were separated from mammals by having wings and laying eggs and by a number of other properties. The principal point in doing this work is that it simplifies our thinking about the next bird we meet. As soon as we recognize him as a bird, we have a number of expectations about him which are likely to be correct.

Objects can be classified in a number of different ways. The trick is to find the most useful one. Usually it will be some simple property which a large number of objects have in common and which enables us to predict a good deal about how each member in the class will behave. The bird example is so obvious and apparently simple that perhaps it obscures rather than illuminates the subtlety and power of the procedure. To get a little closer to the heart of this important matter, let us look at Newton's feat of abstracting the ideas of mass and force from the varieties of motions observed on earth and in the heavens by his predecessors.

Even though Galileo was a very great man indeed and devised most of the experiments that led up to the basic ideas on which the laws of motion are based, he never quite reached these ideas himself. The trouble he had was, in principle, the same one that confronted us when we first noticed our potato sprouts. Every event in nature is the result of a large number, perhaps an infinite number, of other events. Some are certainly more important than others and it is the job of the scientist to find out what they are and arrange them in order of importance. Just as the potato sprout is conditioned by light, temperature, and the availability of a number of different chemical elements, so the motion of an object is the complex result of gravity, the motion of other bodies with which it comes in contact, the resistance of the air in which it moves, the

shape and roughness of its surface, and so on. What Newton (with the help of Galileo) managed to do was to stand back from the entire situation and say that most of the particular properties of bodies—their size, shape, color, and roughness—are relatively unimportant insofar as motion is concerned. Furthermore, motion is not an intrinsic property of objects but is imparted to them by outside influences. Finally, Newton invented two ideas which he then pointed to as the really essential elements in the motion situation. The first of these is the idea of mass, which he regarded as a property of all real objects. The second is the idea of force, which acts on the masses. As we saw in Chapter 1, these two abstractions could be combined in the equations which formed the basis for understanding all the types of motion known until the time of Einstein.

The odd and somewhat upsetting part of the whole situation is that it is extremely difficult to be entirely clear about just what mass and force really are. In point of fact, they can be successfully defined only in terms of each other. The only way we can know what a given mass is is by applying a given force to it and vice versa.

In any case, they didn't exist before Newton thought of them. When we ask ourselves how he managed to think of them, we find that he essentially "pulled them" out of a large number of instances of particular motions or movements of particular bodies. In much the same way, the idea of "birdness" was pulled out of experiencing large numbers of individual birds. We therefore call such ideas "abstractions," a word derived from the Latin for "pulling out." The weight of opinion seems to be that abstractions are best understood as inventions of the human mind and that their validity depends primarily on their usefulness

in describing relationships between events.* In any case, it is clear that they play a very important part in the development of science. Perhaps one of the best ways of assessing the importance or greatness of a scientist is to judge him by his ability to invent useful abstractions. The original idea of the gene, or even of a reflex, was essentially an abstraction similar to the idea of mass, although they are both somewhat less abstract and less general in their application.

The capacity to make useful new abstractions is without doubt the rarest and most important capacity man has. Abstractions of the generality of those given us by Isaac Newton are so rare that they seem almost miraculous. One of the really captivating qualities of some types of abstractions is the ease with which they can be fitted into mathematical formulas. Among other things, this saves an enormous amount of time and effort in the laboratory since we can try out a large number of possible cases in symbolic terms before selecting the most promising ones for experimental test.

As science develops, it keeps encountering situations of greater and greater complexity in which the tried and true methods of dissection and isolation of variables become more and more difficult to apply. Such problems underlie some of the differences that separate the physical from the so-called "life sciences" and bear on the possibility of someday developing true sciences of social and political behavior. We shall, therefore, say a few words about two or three different kinds of complexity and the different ways that have been devised for dealing with them.

* An entirely different view of the status of abstract ideas was taken by Plato and the "realist" school of medieval philosophy. It continues to exist in respectable circles today, but it is not held by many scientists.

In the first place, there are apparently complex situations which really aren't complex at all. They can be dealt with simply by breaking them down into their constituent parts, studying each part separately, and adding up the results. To explain what is meant by this, let us consider the motion of a bullet fired from a gun. Superficially this appears to be a very complex matter, but it really is not because it can be broken down into a series of more or less isolated forces each of which can be studied by itself. The bullet is acted upon first by the explosion of the powder, then by the friction inside the gun and the twisting effect of the rifling. Throughout its flight it is acted on by gravity, the varying resistance of the air, the extra forces generated by the wind, and the Coriolis force resulting from the earth's rotation. The effects of each one can be studied in isolation and then simply added together in order to plot the bullet's entire course. The force of gravity is not much affected by the strength of the powder or the resistance of the air; nor do any of the other forces behave differently from the way they would if they were acting all by themselves.

There are other sorts of complex situations which are difficult to break down and analyze in this bit-by-bit fashion. The first class has been called "disorganized complexity" by Dr. Warren Weaver. In such cases a large number of events are connected with one another in such a way that simple "cause and effect" analysis becomes impossibly cumbersome. For example, anyone who has studied physics knows that it is a relatively simple matter to predict what will happen if one billiard ball strikes another at a given spot and with a given speed. It is only a little more difficult to predict what will happen if there are three balls on the table. Increase the number much beyond this and the original method of dealing with the problem becomes in-

applicable in practice, because the balls begin to run into one another too frequently. Methods have, therefore, been devised for giving the probable results of movement within the system in terms of the number of balls which will hit a given length of cushion in a given length of time, the total number of impacts of all the balls involved, and so forth. By sacrificing one's interest in the behavior of an individual ball one gains a grasp of the behavior of the total system which will be accurate enough for many purposes.

A practical example in everyday life is the prediction of the number of automobile accidents over a given weekend. It is, of course, impossibly difficult to predict when or where a given driver in a given automobile is going to run into another. Nevertheless, the National Safety Council can tell with grisly accuracy how many people are going to be killed next Labor Day. Similarly, the physicist cannot tell which individual radium atom is going to break down into lead and radiant energy, but he knows very accurately what proportion will do so in any selected length of time. Indeed, much of our modern knowledge of the nature of matter has been made possible by the development of statistical methods for analyzing this type of situation.

It is much more difficult to analyze what Weaver calls "systems of organized complexity." In such systems the parts are so closely interrelated that a modification in any one of them is likely to modify the behavior of all the rest. Living organisms provide the best examples of such systems and it is precisely their organized complexity that contributes most to making the life sciences different from the physical sciences. The parts of the human body are much more closely interrelated than the atoms in a gram of radium or the automobiles on the highways of the United

States. A single pinprick on the tip of a finger may give rise to movements in almost all the muscles of the body, to changes in blood pressure, heart rate, sweat secretion, the movements of the intestinal tract, and so on. The particular pattern of response will be different depending on circumstances, such as the number of times one has pricked his finger before, whether or not one is holding something valuable and fragile in the hand that is pricked, whether or not there is someone nearby who is known to object to displays of emotion, and so on.

Every one of the events elicited by the pinprick tends to elicit still other events which react back on the earlier ones. The sudden withdrawal of the arm upsets the balance of the body. Readjustments are made by the other arm, the legs, and the trunk, and messages are sent from these areas back to the original hand and arm which further modify their behavior. The sudden rise of blood pressure calls forth other reactions which keep it from going too far. The list of actions, reactions, adjustments, and readjustments is almost literally endless, for the total experience leaves memory traces in the nervous system which make it very likely that one will avoid pinpricks more easily in the future and react differently to those that do occur.

Highly organized systems of this type appear to develop what might be called a "life of their own" and have led to the speculation that an organism or "whole" is more than the sum of its parts. No one has yet succeeded in developing a very good method for studying wholes as such, without breaking them down into their parts. At present the subject constitutes a sort of borderland between science and philosophy. Two of the most obscure parts of this domain are the phenomena of consciousness and free will. Their very existence is often denied by orthodox scientists, but there is hardly anything that seems more

obvious to us as a matter of subjective experience. The future of the life sciences holds many challenges but perhaps no greater one than the resolution of this paradox—the clear subjective existence of consciousness and its inaccessibility to objective description.

From time to time some scientists have been either so distressed over the difficulty of understanding systems of organized complexity or so overawed by the mystery of life that they have suggested that life processes differ in some basic way from the phenomena studied in physics and chemistry. This school of thought (sometimes known as vitalism) has always been handicapped by its inability to state its beliefs in a form susceptible to experimental test. Conversely, the so-called mechanistic or mechanical view of life has produced a long series of experiments which have made it possible to explain most, if not all, living processes in terms of antecedent events of a physical or chemical nature. The early triumphs of the method came in the sixteenth century when such purely mechanical matters as the movements of the arms and legs were found to obey the physical laws of motion. For example, considerable pleasure was evoked by this school in noting that the various bones represented levers of all three classes. The vitalists then erected their defenses on a chemical point and said that only living things could synthesize certain sorts of substances with carbon as one of their important constituents and known as organic compounds. The German chemist, Wöhler, demolished this barrier by synthesizing urea in 1828 and now there seems to be no limit to what can be made in a test tube. After Wöhler, a long train of investigators demonstrated that living things precisely obey the laws of conservation of mass and energy characteristic of the nonliving world. Remnants of the opposing vitalistic view still crop up from time to time in such

popular books as the recent *Calories Don't Count,* but they have no standing in the scientific community.

In the present century, the opposition to mechanical explanations has centered on the problem of growth and differentiation of individual organisms and the evolution of new species. It is admittedly not very easy to explain how a single germ cell determines the development of a complete and highly complicated organism. Early in this century Hans Driesch further complicated the problem by showing that in certain lower forms (the sea urchin, for example) a single cell of the adult animal is capable of developing a completely new individual. He and some other biologist found this phenomenon impossible to understand on mechanical grounds and returned in effect to Aristotle's notion of "final causes," which states that in some way the oak is the cause of the growth and development of the acorn. Again, however, this view proved unproductive of new experiments giving clearer insight into the problem.

Conversely, the plodding and unimaginative mechanist has continued to devise better ways of looking at the individual cell and of guessing how the blueprint of the developed organism is engraved on its nucleic acids. We are still far from a complete picture of how the process of differentiation and development is timed and guided, but every attempt to explain it in terms of antecedent events has given us new knowledge. The converse attempt to interpret it as the working out of a future purpose has only served to stop people from having useful thoughts on the matter. This is the primary reason that purpose has become a "bad word" among scientists.

Admittedly the most complex behavior of living systems at present eludes mechanical analysis. Nevertheless, progress in analyzing such systems without interfering too

seriously with normal function continues to be made. The recent development of complex computing apparatus holds out further hope for studying the behavior of complex, closely coupled, multivariable systems.

4

Kinds of Scientists

As we found in the last chapter, all science is characterized in part by close observation of isolated details of what later is made into a large, comprehensive picture. The techniques for observing different sorts of details vary enormously. It is this fact that has led to *specialization,* that emphasis on knowing more and more about less and less, which is thought to be so characteristic of the scientific age.

As I will try to show later, the separate paths of scientific specialization have a paradoxical way of converging back onto a final common path, a phenomenon which is one of the encouraging but insufficiently recognized features of modern scientific development. In practice, however, anyone entering science must still do so along one of the fairly well beaten tracks.

In the first instance, specialties in science seem to have arisen for much the same reason that specialties arose in the arts and crafts during the medieval period. Just as carpenters were people who knew what to do with hammers and chisels, anatomists were scientists (really physicians) who were good with scalpels and scissors. Galileo and even Leonardo were employed as engineers, a profession which naturally turned their attention to mechanical problems and investigation into the strength of materials.

Even as late as the French Revolution, Lavoisier laid the basis of modern chemistry, in part because of his responsibility for providing the French Army with gunpowder. A little later Count Rumford was led to the formulation of one of the major laws of thermodynamics by observing the heat produced while he was boring cannon.

Science as a vocation emerged in the nineteenth century as universities slowly came to feel that natural science might reasonably aspire to sit side by side with Latin, Greek, and mathematics. The early unspecialized chairs of natural philosophy shortly gave way to separate professorships of physics, chemistry, and biology. By the end of the century, physics had broken up into light, heat, mechanics, statics, and electricity; and chemistry into physical, organic, and inorganic. Biology already revealed a cleavage between botany and zoology, but for the most part it was dominated by the necessity of identifying and classifying the infinite variety of species in which life presents itself and aligning the results in terms of Darwin's theory of evolution. In addition to the three major scientific disciplines and their recognized subdivisions, the subjects of astronomy and geology achieved independent status fairly early.

By and large, these differentiations, like the earlier differentiation of the practical arts, occurred on the basis of the tools required by the various disciplines. These include actual physical tools such as microscopes, precision balances, timing apparatus, and colorimeters, and intellectual tools of which perhaps mathematics was the most important. Until approximately the last quarter of the nineteenth century, physics and astronomy were the only scientific disciplines that really required a mastery of advanced mathematics. But about this time, chemistry began to be interested in the quantitative details of chemical reactions,

and mathematics became part of the chemist's requirements also. Today many young people who want to go into science but who regard themselves as incapable of mathematical thinking elect biology, but their days are probably numbered. As the older professors of biology, who don't know any mathematics themselves, retire, the younger "molecular biologists" will probably prevail upon the dean's office to require at least elementary calculus as a prerequisite.

There is still a great deal of specialization based on skill in using certain types of apparatus, but this too may begin to disappear as things like electron miscroscopes, oscilloscopes, ultracentrifuges, and so on lose their tricky custom-made character and become standard mass-production machines with a high degree of reliability and with many automatic control features.

In addition to the major scientific specialties—physics, chemistry, and biology—which appear in all school catalogues, there are a number of interesting satellite subjects. Geology, archeology, meteorology, oceanography, psychology, and anthropology are some of the better known ones. All of them employ the general methodology of science and draw on one or more of the basic scientific disciplines for methods and ideas. It would take us too far afield to discuss each one in detail, even if I were able to do so. In practice the individual should make his choice of one of these satellite specialties or of one of the subspecialties of the major triad only after considerable exposure to the basic fields themselves.

Although we do not intend to describe every minor specialty in detail, it may be worthwhile to provide some comment on what was once thought to be a major distinction between the life sciences, on the one hand, and the science of nonliving objects, on the other. As we found

in the last chapter, living things are the examples par excellence of systems of organized complexity. This fact in itself makes their study rather different and in some ways more difficult than the investigations of the simpler systems studied by classical physics and chemistry. Not only are living systems typically complex, they also behave in rather different ways over time. Most physical systems are reversible in the sense of the homely proverb that everything that goes up must come down. By and large, the same equations are used to describe the upward and downward motions. All that is necessary is to change the sign from positive to negative. In the same way chemists can make oxygen and hydrogen combine to form water and can then turn around and split them apart again.

Living things tend to go in one direction only. Typically they grow from a very small cell to a very large group of cells. The cells themselves differentiate into special tissues and organs. Once such differentiation proceeds beyond a certain point, the cell can't go back again to its primitive state. Finally deterioration and death set in, but they are not the opposite of birth and growth in the sense that falling is the opposite of rising or reduction is the opposite of oxidation.

Perhaps the most distinctive feature of the living world is the process of evolution whereby entirely new organisms of apparently ever greater complexity are constantly being created.

In the past these differences in the content of the basic physical sciences, on the one hand, and the biological sciences, on the other, led to considerable differences in procedure and to quite obvious temperamental and intellectual differences in the people who entered the two fields. Now the separation between the physical and the biological sciences is becoming increasingly artificial. For

example, the growth of crystals may be thought by some to bear a kind of resemblance to biological growth. Somewhat more relevant is the recent work on the differentiation of the chemical elements and the evolution of the universe. Here the physical scientist seems to be coming face to face with the kind of increase in complexity that has long challenged the biologist. Other points of contact are developing between the mathematicians, who design and program modern computers, and life scientists interested in the function of the nervous system. In the long run, biologists will become more like physicists and physicists will think more like life scientists. Finally the differences between the two great branches of science will in all likelihood wither away.

A few years ago it would have been easy to draw a distinction between the physical and life sciences on the basis of their attitudes toward the principle of "simplicity." Until very recently physics and chemistry seemed primarily concerned with finding simplicity and order in what appeared at first glance to be complex and diverse events. In fact, as scientists and philosophers tried to answer Pilate's famous question, "What is truth?" they became more and more interested in the possibility that simplicity and the kind of beauty that emerges from simplicity are in fact the best evidence for the "truth" of any scientific statement. The classical case was found in the almost immediate acceptance of the Newtonian conception of the solar system. It is entirely characteristic of this close interrelationship between scientific and esthetic truth that one of the greatest poets of Newton's time described the latter's achievement in the following way:

> Nature and Nature's laws lay hid in night:
> God said, Let Newton be! and all was light.[1]

We have already seen that in our century the light turned out to be somewhat less clear than Pope thought, but the point to be made here is concerned with one of the interesting side effects of the change from Newton to Einstein. Men began to ask themselves why they had been so sure that the Newtonian theory was "true." It now seems quite clear that one of the really important reasons for preferring Newton to Ptolemy was the greater simplicity and beauty of the Newtonian scheme. Indeed, as Professor Edwin A. Burtt has shown,[2] the heliocentric theory of Copernicus was adopted by most mathematicians and astronomers at a time when it was no more useful for predicting eclipses and other heavenly events and actually less consistent with certain other empirical observations (for example, the absence of stellar parallax) than was the classical earth-centered theory.

The idea that the simpler of two possible explanations is the best is a very old one and was much used by the medieval logicians. Such aphorisms as "Nature does nothing in vain," or "Nature always goes by the most direct route" probably go back to ancient times, and modern physics has leaned very heavily on the same principle.

The biologist is a good deal less certain about the principle of simplicity as a guide to investigation or a criterion of truth. In the first place, life presents itself in an almost bewildering variety of forms from the bacterium to the whale. Each species in this endless variety arose apparently as a solution to a single common problem—"how to survive in a hostile world." Each species adapts itself to a particular part of the biosphere by developing a particular set of attributes. The biologist has an intense interest in these particularities and is often captivated by what he can't help calling their "ingenuity," but he doesn't find them simple.

Even within a given organism, closer study shows an almost bewildering complexity of chemical and physiological reactions. Often there are alternate ways of accomplishing the same result. For example, most cells have two sets of reactions for producing energy, one for use when there is an abundant supply of oxygen and another for when oxygen supplies run low. A still uncounted number of hormones are involved in the business of conceiving, bearing, and nourishing offspring, and the differences among mammalian species in the character of the oestrus cycle and the period of gestation are almost as numerous as the species themselves.

The idea that nature does things in simple ways is hard to abandon, however. I remember attending a lecture twenty-five years ago given by the foremost student of the female sex cycle. As I was leaving, the chief of the laboratory I was then working in drew me aside and said, "Bob, the scheme he outlined on the board just can't be true; nature wouldn't be as complicated as that." Since that time, the lecturer's proposals have been amply verified and many further complexities have been added.

The fact that most physical phenomena can be reduced to relatively simple formulas, while most biological phenomena are complex and various, has meant in the past that physicists and biologists have been rather different sorts of people. As mentioned above, physicists have had to know more mathematics, a fact which almost immediately set them off from other men. It also made it difficult for physicists to admit that other scientists were as bright as they were themselves. The physical scientist sought and often found beauty and what he called elegance in the simple relationships revealed by his world. The biologist found his esthetic satisfactions in quite a different

way. A far more earthy and human type, he had frequently spent his youth watching birds or catching butterflies. He found an immediate and daily pleasure in the flash of red on the blackbird's wing, the beauty of the twilight song of the wood thrush, the metamorphosis of a slimy caterpillar into a magnificently bejeweled moth. Frequently he became a collector, and gave his life to describing and classifying the myriad forms in which life presents itself. Slowly a certain order did emerge from all this variety as the work of the classifiers gave rise to one of the great scientific generalizations—the idea of evolution. But the typical biologist still gets his most immediate pleasures from contemplating particular bits or pieces of life that present themselves immediately to his senses. Today, perhaps, the blackbird's wing and the jeweled moth have given way to an almost perfect photograph of a cell taken with the electron miscroscope, but it is the immediate sensory experience of beauty that sustains most biologists in the often frustrating task of untangling the complex network of interrelationships which is life.

The difference between the two broad fields that deal with living and nonliving matter is also related to another difference in the people who pursue them. By and large, physicists seem to make their major contributions relatively early in life. What the patent office calls "a flash of genius" seems to inspire them to predict the existence of a new particle or to develop a new picture of the atom while they are still in their twenties or early thirties. The rapidity with which some physicists have established their scientific reputations has permitted some of them to become interested in extending their speculations into other spheres in the hope of providing an orderly understanding of the universe in general. Although the statistics are not easy to come by,

it appears that more physicists and mathematicians than biologists have spent their later years in pursuing philosophy and even theology.

Biologists, who, as a matter of fact, are often not as bright as physicists in an IQ sense, take more time to make their most significant contributions. Perhaps they also lack the capacity for flashes of genius. Equally, or perhaps more likely, the more gradual onset of productivity is a function of the need to master a lot of detailed data as a preliminary for coming up with a new thought. The variety and the interrelated complexity of life results in masses of data—details of anatomy, details of chemical reactions, details of environmental relationships—all of which tend to swamp the beginning student. If he is good, however, a growing mastery of detail is accompanied by a growing intuitive feeling for the way life works, a kind of biological wisdom which ultimately forms the basis of his creativity and enables him to become the leader of a school. Psychologically secure in his accumulated wisdom, taking delight in his daily sensory contacts with the stuff of life, schooled to tolerate the many obscurities and ambiguities of his subject, he seems to have less need than the physicist for the single overarching generalization hopefully designed to make sense out of everything.

The foregoing lyrical descriptions are in the nature of what the sociologist calls stereotypes and perhaps reveal more about the author than they do about the present nature of physicists and biologists. Both fields are changing rapidly and in many ways are tending to merge with each other. The peculiarly biological phenomenon of growth finds at least a rough parallel in the growth of physical crystals. Recent work on the differentiation of the chemical elements and the evolution of the universe has begun to entangle the physicist in the kind of intellectual problem

that has long puzzled the biologist. The neatness and order that have been the hallmarks of physics and chemistry have suddenly disappeared in a welter of what are seriously referred to as "strange particles." In one of those ironies which makes the pursuit of science a sure guide to Christian humility, this embarrassing shower of inexplicable particles came out of the atom just when men had begun to feel that they had solved the problems of the structure of matter.

A few years ago, because of the remarkable advances that the past fifty years had brought to the understanding of matter, physicists were on the point of deciding that their science had reached the kind of semipermanent plateau which Newtonian physics had inhabited for 200 years. Further experiments were expected to tie up a few loose ends and uncover a few more particles which would fit into the theory already worked out to receive them. But the experiments proved to be far more productive of new particles than anyone had predicted.[3] Worse than that, it has proved very difficult to fit these unexpected items into any reasonable theory. How devastating this has been to the physicist's traditional sense of simplicity, order, and beauty may be judged by a remark made by the great Enrico Fermi. Shortly before his death a few years ago, he was overheard to say that if he had known what was going to happen to physics, he would have gone into botany instead!

Oddly enough, just as physics seems to be losing its orderly simplicity, botany and biology generally seem to be gaining it. As a result, many former physicists are actually abandoning physics and going into what is now known as the field of molecular biology. Even more young men and women, who might twenty or even ten years ago have chosen physics or chemistry as a career, are now electing biology instead.

What has happened to make biology so attractive to the orderly sort of mind? In a word, the probability has emerged that many—if not all—of the puzzling characteristics of life will find their explanation in the shape of the very large molecules which form the genetic material of the chromosomes. These molecules are known to be long linear chains of substances called purine and pyrimidine bases (linked together with a sugar and some phosphoric acid). Ordinarily there are four different bases available and it is the order in which they are put together that apparently determines just about everything that happens in the making of any living organism.

Roughly two hundred years of observation have provided a good descriptive knowledge of what happens as a single egg cell grows, divides, and differentiates into skin, gut, bones, muscles, nervous system, and glands, but there have been only vague clues as to how this intricate process was guided and timed. It is clear enough that each stage in the process starts at a particular point and stops when the organ or system in question reaches its appropriate size. In the case of man, certain stages like bone growth proceed for as long as 20 years. Others, like the differentiation of the nervous system, are finished shortly after birth. The phenomena of adolescence wait 10–15 years even to get started. But how does all this come about? What determines the time at which some processes stop and others begin? The key to understanding these really wonderfully coordinated events now seems to lie in the genetic code which also, of course, determines the hereditary differences among species and between individuals within a single species.

Less clear at present, but probable and provocative, is the idea that certain responses to environmental influences may depend on changes in the genetic code of specialized types of cells. The development of immunity to infectious

disease may be traceable to the ability of certain cells in the lymph nodes to alter their genetic code so as to direct the manufacture of protein antibodies. Similarly, some forms of cancer may be related to alteration of the code by viruses, radiation, or chemical agents.

The possibility of tracing all these varied and highly significant phenomena back to a single molecular source is as challenging as any of the new frontiers opened by science in the past. It is no wonder that biology is now beginning to attract many of our most vigorous and imaginative young minds.

Notes

[1] Alexander Pope, "Epitaph Intended for Sir Isaac Newton."

[2] *Metaphysical Foundations of Modern Physical Science,* New York, Humanities Press, 1952.

[3] M. Gell-Mann and E. P. Rosenbaum, "Elementary Particles," *Scientific American,* 197 (1), 72–88, July, 1957.

5

The Scientist and the Engineer

EVERYONE KNOWS THAT THERE IS A CLOSE RELATIONSHIP between the progress of science and progress in the practical arts. In the case of engineering and medicine, the relationship is so close as to lead to some confusion in regard to the real roles of the practitioner and the scientist. We shall discuss this matter in terms of the engineer, but much of what will be said would apply equally well to the physician.

Unfortunately, it is very difficult to discuss the difference between two things without implying in some way that one is better than the other. It is not the intent of this chapter to make invidious distinctions of this sort. In fact, I would prefer to avoid discussing the subject at all were it not for the possibility that the student who does not realize that differences do exist may find himself going to the wrong school and expecting the wrong sort of satisfactions in later life.

The most significant difference between the scientist and the engineer lies in their respective attitudes or styles of life. It is not a matter of intellectual capacity; the first-class engineer is no dumber or brighter than the first-class scientist. He may well be just as imaginative and just as "crea-

tive," but he does tend to find his satisfactions in different ways. Sir Francis Bacon once said that "we cannot command nature except by obeying her." Broadly speaking, the engineer gives most of his attention to the first part of the statement, the scientist is more concerned with the last part. The scientist discovers the rules and the engineer plays the game. The typical scientist begins to lose interest in a subject almost as soon as he understands it. For the engineer this is where the fun begins, since he gets his satisfaction by using new ideas to make new things. In large part this satisfaction derives from creating a new physical entity that can do something that has never been done before, but the engineer is also likely to be pleased that the device contributes to the welfare and happiness of human beings. Many so-called pure scientists, on the other hand, take pride in the fact that the work they are doing "has no obvious practical application." It may be easier to understand this attitude if we regard it as the modern version of the snobbery of the Chinese aristocrat who let his fingernails grow to ridiculous lengths and bound the feet of his women to demonstrate that they didn't have to do anything useful in order to enjoy their high position.

Before we become too critical of the scientist, it would be well to remember that many of the most "useless" of his discoveries turn out in the long run to have the most far-reaching practical benefits. Perhaps his sense of superiority is an essential though unattractive device to protect him from the need to produce some new thing simple but attractive enough to gain immediate popular applause.

The scientist is, by and large, more skeptical than the engineer. His primary obligation to advance knowledge necessarily causes him to question the validity of existing knowledge. For him, doubt is the beginning of wisdom. Not so the engineer; like other practical men, he has to

make decisions that have immediate effects that everyone can see. Typically he has to make these decisions right now on the basis of existing knowledge. If he isn't to be paralyzed to the point of inaction, he must be confident rather than doubtful about the validity of his basic engineering principles.

Hippocrates, speaking as a physician and not as a medical scientist, described the dilemma of the practical man very well when he began his famous aphorism with the following words: "Life is short and Art is long, the crisis is fleeting, experiment risky, decision difficult." In modern English this might read as follows: "You have to do something right now if this patient is going to get well and you have to do it on the basis of existing knowledge. It takes a long time to make substantial advances in knowledge and it is very dangerous to try something new in the treatment of a particular case."

A medical scientist would have an entirely different attitude. He would be likely to say, "It's pretty obvious to me that you really don't know very much about what's wrong with this patient and I doubt that you can do much for him. Why not forget about him for the moment and do some of those experiments which frighten you so much, so that at least the doctors who come after your short life is over will know what they are doing?"

Clearly we need both sorts of people in the world and it would be foolish to ask which is better. It is well worth noting, however, that the practical man's necessary confidence in the existing state of his art tends to make him a conservative; or perhaps it is equally valid to say that conservatives tend to become practical men. This attitude goes well beyond their professional life as is demonstrated by the well known political conservatism of the American

Medical Association and the large number of engineers who vote the straight Republican ticket.

From the student's point of view it is important to note that this confidence in what Professor Galbraith has called "the conventional wisdom" is reflected in the curriculum and manner of teaching in many of our engineering schools. The situation is changing somewhat, but it is more frequently true than not that courses in engineering still regard scientific generalizations as laws of nature. The attitude is that these laws and their corollaries are there to be memorized as a basis for future action. After all, there is a massive amount to be learned and you had better not waste your time questioning what better men than you have figured out. Sure it's tough and a lot of you are going to flunk out, but those of you who survive will always be proud to have graduated from good old Rule of Thumb Tech.

In recent years many young people who have not troubled themselves to draw a distinction between science and engineering have suffered a rude shock when they have encountered the attitude described in the preceding paragraph. This shock is likely to become even greater and more widespread as more and more students arrive in engineering schools after having enjoyed the rapidly improving science courses in high school. Already there is general concern over the fact that enrollment in undergraduate engineering schools has been falling off in the last few years. A phenomenon such as this is always difficult to explain, but there is more than a suspicion that part of the trouble arises in the unimaginative, essentially unscientific atmosphere in many of our engineering schools.

However valid the basic distinction between the scientist and engineer may be as a matter of current fact, it may be unwise to accept it uncritically as a guide to policy. We

have already seen, for example, that many early scientists were employed as engineers or physicians or even as astrologers and alchemists. Pasteur was a great theoretician as well as a man of intense practical interests who spent much time saving the silkworm industry in southern France and in trying to make French beer better than German beer—perhaps his only real failure.

Today our rapidly growing technology demands the closest sort of cooperation between scientists and engineers simply because the existing state of the art is not sufficient to allow us to build new devices, the need for which is clearly defined. For example, the engineer who is asked to design a spacecraft cannot rely wholly on well recognized methods and materials. The stresses involved in space navigation, especially the high temperatures generated by flight at high speeds, demand the development of new materials which, in turn, demands new knowledge of the molecular structure of metals and ceramics. So-called basic research is thus keyed directly into the engineering process. Even if the engineer doesn't do the basic research himself, he must adopt a much more flexible attitude toward conventional wisdom and new knowledge than he was trained to have in the past.

Recognition of these facts is leading many of our better engineering schools to revise their curricula so as to decrease the dependence on more or less brute memorization of engineering rules and regulations and to increase the emphasis on methods for uncovering new knowledge. Insofar as graduate training is concerned, this movement began over thirty years ago and is now well advanced in such institutions as Cal Tech and M.I.T. Indeed, the pure science departments in the graduate schools associated with the best engineering schools are fully comparable with those in the best universities. However, only in the last few years has

the scientific attitude really begun to percolate down to the undergraduate level.

Finally, it should be recognized that there are several levels of activity in both science and engineering. First, as in any branch of human endeavor, there is a good deal of purely routine work to be done that puts no particular strain on the intellect or the imagination. There is little if any difference between science and engineering insofar as gathering data by well understood methods is concerned. Both fields require the performance of many chemical and physical tests to provide the data necessary for reaching their objectives. It makes very little difference at the data-gathering level that in one case the results will be used to understand nature while in the other they will be employed in designing a new device.

The personnel needed at this level need special training to develop the required skills. In the past the majority of engineering and scientific technicians were high school graduates who received specialized training on the job as draftsmen, chemical analysts, and so forth. Increasingly the modern technician is a college graduate who has majored in one or another of the basic sciences.

The next level includes the majority of typical scientists and engineers. These individuals are engaged in developing the ideas, filling out the designs, and applying the rules worked out by the highly original minds at the top of their respective pyramids. It is at this level that the distinctions between scientists and engineers outlined above are seen at their clearest. The great bulk of professional engineers are to be found at this level—building bridges, designing new automobile engines, supervising production lines, working out new chemical syntheses, and developing whole new industries on the basis of such new technologies as electronics. Increasingly the engineer must work as part of a large

team devoting his energies to designing or developing one or another essential part in a complex product or industrial process. Even though most engineering results in some new thing, the activities leading to it are already well known. The average engineer is therefore involved in applying well known rules and standard tables in as original a way as he knows how to do. It must be admitted also that the scope of his originality encounters a variety of constraints, depending on the state of the industry in which he is working. Generally speaking, the classical fields of civil, mechanical, and chemical engineering are pretty conservative in outlook. The basic principles of building bridges and dams are well understood, and the product appears to meet existing needs very well. In the large industries, of which the manufacture of automobiles is perhaps typical, the heavy investment in existing designs tends to make management reluctant to encourage significant innovations. The engineers employed in industries of this character must perforce confine themselves to refining details within a well established framework. It is significant in this connection that the European automobile makers, with their smaller markets and relatively less massive investments, have provided many more basic innovations in automotive design than the large American makers have.

There seems little doubt that the scientist at this same intermediate level enjoys a good deal more freedom of action than the typical engineer. He may have no more intellectual capacity and no more intrinsic originality, but his situation is likely to be such that he can express what he has more easily. In the first place, he is much more likely to be working by himself or as a member of a small team in which his voice will be more easily heard as the team's overall objectives are being mapped out. In the second place, he is much more likely to be working in a university

or research institute with a tradition of academic freedom that protects whatever sparks of originality there may be in the faculty. Even if he is employed in a government or industrial laboratory, as many scientists increasingly are, he will enjoy more independence than most of his engineering colleagues. Management has begun to admit, however reluctantly, that they get more out of their scientists by leaving them alone than by trying to order them around.

Nevertheless, it would be wrong to think of the typical scientist in this intermediate level as constantly generating brand new ideas about nature. A great deal of scientific work is concerned, in fact, with exploring how far a new idea generated by somebody else to explain one set of phenomena can be used to explain another closely related set.

For example, back in 1921 Professor Otto Loewi, of the University of Graz in Austria, became interested in explaining the by then well known fact that stimulation of the vagus nerve results in slowing of the heartbeat. It had always been somewhat of a puzzle that an increase of activity in a nerve results in a decrease of activity in the organ which it controls. One possibility that interested Professor Loewi was that the nerve liberated a chemical which in turn depressed the heart, since several substances were already known to affect the heart in this way. A compound known as acetylcholine seemed to be a particularly good candidate and he spent some time thinking up ways of demonstrating that such a substance was actually liberated by the nerve in amounts sufficient to have the desired effect. As he later told the story to many of his friends, he woke up one night with a clear idea of just what to do and jotted down an outline of the proposed experiment on a pad he kept by his bedside. Unhappily, he found he could not read his notes the next morning. (Physicians traditionally have very bad handwriting and it is even worse if they are very

sleepy.) A night or two later he again had the same dream. Taking no chances this time, he arose immediately, went to the laboratory, and performed the experiment which was to bring him a Nobel Prize some fifteen years later. First he arranged an artificial circulation to and from the heart of a frog so that he could collect the fluid that emerged from it. He then took this fluid and placed it in a second heart and recorded its rate. The fluid collected from heart A under normal circumstances resulted in no change in heart B. Fluid taken from heart A during stimulation of its vagus nerve, however, resulted in marked slowing of heart B.

The way was now clear for other workers of less imagination but comparable skill to demonstrate that this was not an isolated phenomenon, unique to frogs and vagus nerves, but common to a wide variety of other nerves and other species. It would take a very large book indeed even to outline all the experiments that have been done to show that the vagus nerve in all species, both warm- and cold-blooded, does indeed liberate acetylcholine; that not only the vagus nerve but other nerves of the same class which supply the blood vessels, the gut, the bladder, and a number of other organs do the same thing; and that certain other nerves which have opposite effects liberate another set of substances.

A little later it was shown that the nerves to the muscles which move the body also work through acetylcholine, and that the transmission of nerve impulses from cell to cell in some parts of the nervous system also involves the same important chemical. It now seems likely that there are a number of different "chemical mediators," each one of which may have a particular sort of function in the nervous system. Forty years after Loewi the hunt is still on to ex-

plore all the ramifications and implications of his basic experiment.

It would be a mistake to get the impression that the scientists who came after Loewi had nothing to do but apply his technique. With the insight of genius he had actually selected what is probably the easiest case for demonstrating the phenomenon. His followers had to develop more complicated and often more ingenious techniques when they tackled the problem in warm-blooded forms, and in organs which are more difficult to perfuse than are frog hearts.

To get back to our theme of the relationship between engineering and science, we may now observe that the development of the techniques necessary to demonstrate Loewi's phenomenon in other species and in other organs involved the solution of a series of what in one sense are almost pure problems in engineering. Appropriate devices had to be built for providing artificial circulation to a wide variety of organs. Other devices had to be built for recording the mechanical or electrical activity of these organs. Indeed, if you had watched most of this group of workers on many of their working days, it would have been hard to say why they weren't doing exactly what engineers do. As a matter of fact some of them were and are engineers by taste and by training.

The cooperation of electrical engineers became especially important when attention turned to the difficult problem of nerve-to-nerve transmission, since the best way of telling whether nerves are active is to record the electrical currents they generate. These currents are very small and of relatively short duration. Highly refined amplifier circuits and sensitive oscillographs must be used to observe them accurately. Much of the basic technology could be borrowed from circuitry developed for other purposes, radio and TV

for example, but much time and skill are necessary to adapt the basic technology to the specific purpose the experimenter has in mind.

However much of his time a scientist may spend "making like" an engineer, he is still distinguished by his primary concern about the uses for his special devices. In the case under discussion, the overall objective was to explore and extend the generality of the idea of the chemical mediation of nerve impulses. Some scientists get much the same fun that the engineer does out of designing a better gadget; others regard such preliminary developmental work as almost pure drudgery. Both engage in it, however, because in the long run it is the only way to show whether the idea they have in mind is valid or invalid.

When we get to the very highest level of creativity in both science and engineering, our argument for a distinction between the two becomes even more difficult to sustain. The difficulty arises in part because we understand very little about the processes involved in what we call creativity. In one sense almost everyone is capable of making some new thing or having some new idea. Every home craftsman who puts up a new shelf in his wife's kitchen is creating something new. Even a high school theme can contain some new, at least slightly new, thought about a teen-ager's response to a trip to Washington.

The term "creativity" is usually reserved for activity on a somewhat higher level than this. In this discussion we are considering "the very highest level"—the creation of very new and very general ideas in science and the development of very ingenious solutions to engineering problems. In the first category are people like Copernicus, Galileo, Newton, Maxwell, Rutherford, and Niels Bohr. In the second are the unknown inventors of the wheel or the smelting of copper ore, and more modern inventors like James Watt,

Marconi, and, one of the greatest of them all, Thomas Edison.

In both groups the achievement is obviously so great, so unrelated to what has gone before, that ordinary men have difficulty imagining how the deed was done. The individuals themselves are not very helpful in explaining how they did it either. The more self-conscious and introspective may be able to describe the events leading up to the generation of a new idea, but the critical moment seems to elude them. Sometimes it is shrouded in a dream as in the anecdote recounted by Otto Loewi.

Others are impressed by the element of luck that seems to enter into many, if not most, discoveries and modestly pretend that their achievement was nothing more than a stroke of good fortune. Certainly many technical advances have been made because some technician broke a thermometer and added some unplanned mercury to a reacting mixture, kept the gas on for too long a time, or simply neglected to throw away a bacterial culture and thus revealed a "new" species with an unusually long growing time. Alexander Fleming is said to have discovered the action of penicillin by observing a clear area in one of his cultures at a spot accidentally contaminated with a bit of common bread mold. In all these cases, however, the phenomenon had probably occurred many times before without anyone's noticing. The act of noticing the importance is the really significant thing. This interaction between chance and the creative human intellect has perhaps been best described by Pasteur in his famous aphorism, "Chance favors the prepared mind."

Still other creative people, especially those with an engineering or artistic bent, entertain the theory that most people are potentially equally creative but are spoiled by the unstimulating and actually inhibiting effects of much

of our regular education. It appears to be true that many unusually creative people in both engineering and the fine arts have had rather spotty and unconventional education. But the other side of this proposition is not so convincing. There are many, many people with spotty and unconventional education who are not unusually creative. There is enough worry about the possibly depressing effects of some of our present methods of education, however, to have stimulated active changes in science and engineering courses, especially at the secondary school and college levels. These will be dealt with in a later chapter.

It may not be too difficult to remove much of the inhibitory effect of education. It is quite another thing to take a positive approach and design a curriculum and teaching materials for the production of creative genius. In fact nobody has seriously tried to do so, since we know so little about what creative genius is. In the field of pure science it is usual to find that the most creative people have had a good standard education. Frequently they have gone on to occupy a series of academic posts. The creative engineer, at least until very recently, has tended to have somewhat less formal education. Edison's formal schooling, for example, was limited to three months. By far the most creative engineer I have personally known left college in his freshman year and didn't return until some years after he had produced his first major invention. These observations lead us to the conclusion that education has relatively little to do with the initiation or cultivation of creativity as such, although it probably is important in shaping the form which the expression of creativity may assume.

The greater academic interests and affiliations of the scientist are probably related to the fact that his principal product is a set of statements about the nature of things. He must, therefore, have more than the usual interest in

the use of words and mathematical symbols, and it is in academic circles that these skills reach their highest levels. Science really doesn't exist until the results have been accurately described to and accepted by other workers in related fields.

The engineer may do much of his mental work in a nonverbal, more or less intuitive way. The first recognizable product is an actual material thing rather than a verbally expressed idea. This tendency to skip the symbolic stage of the creative process is often reinforced by the necessity for secrecy involved in much industrial and military engineering. The engineer is not only less interested and less capable than the scientist in communicating his results; he often finds it unprofitable or even dangerous to do so.

In summary, I hope I have said enough to show that both scientists and engineers come in a variety of shapes and sizes, that there are very great differences in the degree of creativity exhibited *within* each field. Both scientists and engineers may be engaged for much or even all of their lives in essentially routine tasks; on the other hand, either field offers opportunities for the highest forms of creativity. At certain stages in the development of new technological fields the activities of scientists and engineers become indistinguishable.

Nevertheless, there are certain differences in attitude, in style of life, and in the character of satisfaction to be gained in the two fields. These differences are great enough to justify a good deal of self-analysis before a given individual makes a final choice between them.

6

The Social Sciences

UP TO NOW WE HAVE BEEN TALKING ABOUT SCIENCE AS if all it embraced were the physical and the biological sciences. Broadly defined, these two branches of science ought to cover just about everything that is knowable through the use of the scientific method. It has been customary, however, to recognize a separate group of disciplines which deal with certain aspects of man's behavior. Of these the most prominent are economics, sociology, social psychology, and cultural anthropology. History is sometimes included as a science and sometimes regarded as an art. Its classification would appear to be largely a matter of taste. My taste is to exclude a discussion of history in this book on the practical, but perhaps slightly arbitrary, ground that most young people who are thinking of becoming scientists are not as a matter of fact thinking of becoming historians.

Most of economics and sociology are clearly more scientific in method and outlook than history is.[1] Both are primarily concerned with discovering regularities in human behavior; both have developed excellent methods of collecting and analyzing the data generated by such behavior. Certain types of sociologists, especially those concerned with the behavior of small groups of people, have evolved experimental methods of observation. Even economists can

approach the use of experiments in certain circumstances. The Common Market can be regarded, for example, as an instructive though incompletely controlled experiment of the theory of free trade.

Those who remain skeptical about the status of economics and sociology would do well to reflect that these two disciplines are closer to developing a bona fide experimental method than are astronomy, meteorology, or even geology.

Another criterion that has frequently been used to appraise the status of a given field of learning is the degree of precision with which it makes and records its observations. Thus in an older time physics and chemistry were frequently referred to as the "exact sciences"—leaving the reader to infer that all other sciences were somehow inexact or frankly rather messy. It is true that there are some physical and chemical measurements that can be made quite precisely, but, generally speaking, most work in the "exact sciences" is not carried beyond three or four significant figures. This represents an accuracy of 1 part in 1,000 to 1 part in 10,000. Many operations in the practical everyday world are carried out with a higher degree of precision than this. Several parts of an automobile engine are honed to a tolerance better than 1 in 10,000 and some may go as high as 1 in a million. Banks balance their books to an accuracy which is presumed to be infinite.

It is its attitude toward inaccuracy rather than its devotion to precision as such that distinguishes science from other activities. Unlike bookkeepers, scientists recognize the probability of error in every observation they make. They not only recognize it, they specifically state it. The methods worked out for calculating the degree of error inherent in various kinds of scientific statements were briefly mentioned in Chapter 1 and will not be discussed here. The important

point is that scientists are continually aware that some degree of error is inherent in every observation and prediction they make. If they are good scientists, they make every effort to calculate the probable degree of error and state it for all the world to see.

Even with all these precautions, certain estimates of great importance turn out to be even more grossly wrong than expected. Ten years ago the age of the universe was given as 5 billion years.[2] It has now approximately doubled.[3] Economists have long been able to predict the gross national product and a variety of other economic matters with a much higher degree of accuracy than this. The procedures for forecasting elections worked out by the much maligned pollsters are almost always able to predict the outcome of national elections with an error of less than 1 percent. This is a far higher degree of accuracy than that provided by most of the scientific tests used by doctors in taking care of patients.

If, then, the social sciences have good ways of gathering and analyzing data, have developed experimental methods beyond the reach of astronomers or meteorologists, and can make some sorts of predictions more accurately than the classical exact sciences, why are so many people reluctant to accept them as sciences?

Probably the greatest problem faced by the social scientist is the fact that he deals with matters clearly and immediately important to the daily life of human beings. Oddly enough, the natural sciences have so far done more to alter the actual conditions of human life than the social sciences have. But the connection is not immediately obvious. When Faraday read his paper on inductive electric currents, no one, not even he himself, foresaw a world run by electric motors. Today biologists are happily working on the biochemistry of genetics in a way that is bound to

alter our whole attitude toward what is moral and not moral in the field of sexual behavior, but nobody pays the slightest attention. But let a single sociologist point out that as a matter of fact many people engage in sexual behavior widely different from the accepted social and legal norms, and a storm of protest breaks out. Not only are his motives suspect on moral grounds, but his scientific procedures are scrutinized by columnists and reviewers, ministers and college presidents, with an intensity never aroused by the often less precise investigations of the natural scientist obscurely at work in his laboratory. Much perfectly valid scientific study, not only of sex behavior but of such matters as the way voters make up their minds and the balance of trade between countries, is thrown out of court simply because the results conflict with the preconceptions and material self-interest of given groups of individuals.

In addition to their inevitable involvement with current human affairs, the social sciences suffer from the difficulties inherent in the study of systems of organized complexity discussed on page 41. Admittedly, science has not yet developed fully competent ways of dealing with these multiple, variable, interlocking systems. It will be a long time, therefore, before the social sciences can come up with the sort of overarching generalizations that Newton and Einstein gave to physics and Darwin gave to biology. Until they do, they will suffer from a sense of inferiority and inadequate prestige. This lack of prestige and the apparent difficulty of making recognizable progress in many areas of the social sciences have in the past made for difficulties in recruiting the best minds into the field. Most studies have shown that graduate students in the social sciences are at the bottom of the list of scientists as far as the qualities measured by the current IQ test are concerned. Thus the social sciences tend to suffer from a vicious circle: relatively

inferior people do relatively inferior work, which in turn attracts relatively inferior people. Fortunately, there are signs that the circle is being broken. The social sciences are achieving greater recognition and there is now a social science division of the National Science Foundation. Some large private foundations have also joined in the work of redressing the serious financial imbalance which has greatly favored the basic natural sciences since World War II.

Certainly there can be no doubt about the need for understanding more about man's social behavior and of the various institutions he has invented to order his affairs. The natural sciences have provided most of the methods needed for abolishing the hunger, pain, physical disability, and early death which were the lot of almost all men until very recent times. But we are not yet using these tools effectively to alleviate the misery of a large proportion of mankind. We have not yet invented the social and political institutions needed to transfer new techniques rapidly from one part of the world to another. We do not yet know how to organize ourselves to deal with the imbalances which occur when science is unevenly applied to the solution of human problems. Many countries have already encountered the dangers of rapidly lowering the death rate without at the same time controlling the birth rate. The advanced countries in their headlong rush to the more abundant life are cutting down ancient forests, polluting rivers, and even poisoning the air we breathe in our most populous cities. So long as mankind was relatively few in number and could summon only the additional power of a few domestic animals, nature could be left to herself to maintain a reasonable balance. Now the balance of nature, with all its beauty and variety and all its resources for nourishing both the body and the spirit of man, lies at man's mercy.

The progress of natural science therefore makes men

more dependent on one another. If they are to enjoy the benefits of science, they must learn to work harmoniously together, dividing the necessary labors more elaborately among themselves, conducting schools and universities in order to disseminate the necessary knowledge, setting up transport systems to exchange the goods manufactured most advantageously in particular parts of the world, and devising intricate systems of government to keep the whole complex system operating smoothly. Most important of all, social mechanisms are needed for foreseeing and controlling the possibly injurious results of the application of scientific power.

It is the task of the social sciences to supply the organized knowledge of man and his institutions upon which needed social inventions can be based. There is a very great challenge here, and there seems no reason to suppose that it cannot be met by much the same sort of method that has brought such striking advances in the more basic sciences. Man is, after all, a part of nature, and social behavior comes naturally to him; sociology, economics, and political science must increasingly be regarded as sciences just as "natural" as physics and chemistry.

For various practical reasons, however, this book will not have very much more to say about the social sciences. There is a limit to what can usefully be discussed in a given space and there are severe limitations upon this author's ability to describe the social scientist as a career model. But anyone wishing to play a part in developing the science of the future should give some thought to the fields which deal with man's behavior.

Notes

[1] A very readable book by E. H. Carr entitled *What Is History?* gives an excellent account of the method of history which reveals many similarities with what has been said in this book about the methods of science.

[2] *Science News Letter* 63 (1), 5, Jan. 3, 1953.

[3] *Ibid.*, 76 (18), 289, Oct. 31, 1959.

7

How to Become a Scientist—High School Years

SINCE WE BEGAN THIS BOOK WITH A STATEMENT THAT science is merely the elaboration of what a healthy curious child does in order to build up a useful set of ideas about the nature of the world, we should perhaps have entitled this chapter "How to Remain a Scientist." One is reminded here of an aphorism of Hippocrates: "In the first place, do no harm." Applied to remaining a scientist this essentially means, "In the first place, be sure you don't lose your natural curiosity and your ability to draw useful conclusions from observed facts." A good part of the influence exerted on children by other human beings restrains curiosity and independence and replaces them with reliance on the accumulated wisdom of older people. These influences are by no means all bad nor are they necessarily exerted as a result of bad motives. In point of fact, our most characteristic capacity as human beings is our ability to learn directly from other people without having to experience everything ourselves. This ability to profit by other people's experience is of course a great time-saver. It also saves us the pain of having to perform a lot of tests and experiments that turn out badly. Like all virtues, however, the tendency to take other people's word for the nature of things should not be

pushed too far. It is downright disastrous to allow one's own faculty of discovery to atrophy from disuse.

It is true that some societies have succeeded in limiting the growth of knowledge. Through the development of rigid systems of parental, bureaucratic, and priestly authority, such states kept people from learning anything except what their elders and betters told them. If social stability of a sort and long survival are one's only criteria of success, these states were very successful. But if one looks for richness and variety, the creation of new ideas, and better ways of living, one finds that most of these qualities were present only in the early days of the culture. As time wore on and the educational system became more and more successful in turning out just what the teachers and lawgivers had in mind, the less interesting the society became. Furthermore, all such societies ultimately proved incapable of meeting a new challenge from outside. In this sense, a completely effective educational system is both a complete success and a complete failure.

The dangers of an educational system based on the rote memorization of what other people have discovered have long been recognized in the Western world. For several centuries Western universities have actually done a great deal to encourage intellectual freedom and student enquiry. The same spirit has been only fitfully present in primary grades and virtually invisible in the secondary schools. This arrangement required the university to reverse the old metaphor about closing the door after the horse has been stolen. Instead it had to unlock the door after most of the horses inside had died of suffocation.

Several decades ago a growing concern about the stultifying effects of conventional schooling led to the movement known as progressive education. Noble in purpose, this method placed responsibility on the child to choose what

he would learn and to a large extent how he would learn it. The movement has been much criticized and we will not review the arguments here. It probably fell short of complete success because of overconfidence in the ability of the individual child to repeat the history of the human race. In its extreme forms, it also overlooked the importance of self-discipline and the development of emotional and intellectual techniques for sustaining the inevitable drudgery and hard work necessary for carrying to completion any task worth doing.

As a result partly of the progressive movement and partly of a truly remarkable effort to offer primary and secondary school education to everyone, the people responsible for primary and secondary education tended to lose touch with the people responsible for the growth of knowledge in colleges and universities. Methods of teaching received increasing emphasis at the cost of careful consideration as to what should be taught. The content of many courses, especially perhaps in the sciences, slowly became obsolete, or, in extreme cases, disappeared entirely.

As a matter of fact, few elementary or high school teachers have had much contact with advanced work in the sciences. Far too many have had little or no scientific training at all. They are thus in a poor position to reveal the joy of discovery and the beauty of scientific concepts which are the stuff most scientists live by. Instead, if the teaching of science is related to anything at all, it is referred to the world of practical affairs. As a result, physics books have tended to contain less and less about physics and more and more about automobiles. Mathematics has been presented as weighing, measuring, and keeping accounts, with little reference to the pleasures of finding out the hidden relationships between numbers which keep mathematicians intellectually alive.

Very, very fortunately, American students are today living through what amounts to a revolution in the presentation of science and mathematics. Partly because of growing dissatisfaction among schoolteachers themselves, partly because of parental worries, partly because certain university teachers became increasingly restless about the distorted scientific outlook of the pupils who come to them, and partly, I fear, because of Sputnik, schoolteachers and university scientists are working closely together to produce new courses. It is much too early to say just how good these courses are. But there are many good things to say about the process itself and the side effects it has generated. In the first place, the psychological barriers that separated schoolteachers from university professors are rapidly breaking down. The professors are turning out to be much less snobbish and unrealistic than the teachers had feared. The teachers, far from being the complacent, unimaginative functionaries many scientists had pictured, are proving themselves more than anxious to find out what modern science is and to do a much better job of transmitting it to their pupils. Many of them are devoting their entire summers and weekends and evenings throughout the year to attending specially developed institutes that bring school and college teachers together.

Some of the very best scientists in the country have devoted two or three years to the development of new courses for secondary schools. The physicists were the first group, but they have been followed by two groups of chemists and three groups of biologists. The physicists began by asking themselves what they felt were the most important things to know about physics at the present time. Clearly a high school student should not be asked to learn all of physics in one year. On the other hand, it seemed undesirable to expose him to a smattering of knowledge in each of the

many fields of physics. Finally the decision was made to eliminate some fields almost entirely and concentrate on the nature of the atom and the mechanics of motion. We shall not review here the reasons for this choice as they are well covered elsewhere. The important thing is that the group had the courage to limit the amount of material to be learned so that there would be time to get a reasonably full understanding of one very important branch of physics. Equally significant was the decision to present the course in such a way that the student would get a real insight into and feeling for the material to be learned. Whenever possible he would be led into discovering for himself the basic ideas by performing the experiments that gave rise to the ideas in the first place. No scientific statement was to be presented as mere dogma to be memorized and parroted back on the exam. When the student could not for one reason or another arrive at an idea himself, he was at least presented with a careful account of the evidence either in the textbook, in a lecture demonstration, or a carefully prepared movie. The reasons for believing a given proposition were felt to be more important than the proposition itself. Thus the course is designed to show what science is as an active method of discovery, not merely as a static set of generally accepted truths.

Space does not permit discussion of the courses in chemistry and biology which at this writing have not yet progressed to the stage represented by the Physical Science Study Committee's (PSSC) course in physics. The general principles and the procedures followed are in any case much the same. Mention should also be made of the very extensive work undertaken by several groups in mathematics. This is especially noteworthy because of its emphasis on the primary grades. Here there seems to be a very real hope that the imaginative presentation of basic mathematical

ideas is already changing the attitude of many children toward arithmetic. In the past, perhaps a majority have emerged from school with a life-long fear and hatred of anything having to do with numbers. For generations arithmetic has been taught as an arbitrary set of computational rules to be mastered only by the most tiresome sort of drill. Insight into the real meaning of mathematics might come to the near-genius in the class, but little help in this direction was available either from teacher or textbook. Worst of all, motivation and incentive depended on fear of being wrong rather than joy in being right. It is now becoming clear that mathematics can be fun. Best of all, when mathematics is fun, arithmetical accuracy follows almost painlessly.

All this is by way of saying that one of the first steps in becoming a scientist is to go to a primary school where at least some mathematics is taught by one or another of the modern methods. The so-called SMSG courses worked out by the School Mathematics Study Group project at Yale University are the most commonly available.

Some people already in high school will have been fortunate enough to have had a good preparation in elementary mathematics; many others will have learned how to handle numbers in conventional courses without having been permanently damaged. The best students will have found out for themselves how interesting mathematics can be.

Whatever one's background when he gets to high school, the student should certainly continue to take one math course each year. In our best high schools it is possible to gain mastery of elementary algebra, plane geometry, and trigonometry, and to top this off with a sound introduction to the theory of probability and calculus.

What to do with the rest of one's courses will vary according to one's personal tastes and, perhaps even more

importantly, with what is available. If good courses are provided in physics, chemistry, and biology, one is tempted to recommend that the future scientist take all three. Indeed, it would be a very good idea if all future citizens would take all three. We are living at a time in which science bears importantly on every aspect of our lives. Just as Latin and Greek and mathematics were the keys to knowledge when the classical educational pattern was laid down in the Renaissance, the natural sciences are the most important keys to knowledge today. It may still sound a bit prejudiced to say so, but it is nevertheless true, that no man or woman is really educated for life in the twentieth century unless he understands the basic propositions of science. We will have more to say about this later. At this point I only wish to emphasize the importance of getting a good introduction to science at the secondary school level no matter what one is going to do in later life.

There is a good deal of confusion about the order in which the sciences should be taken. A decade or more ago it perhaps made little difference. Each of the three basic sciences could be regarded as more or less a self-contained unit to be studied with little reference to the other two. As set forth in an earlier chapter, however, the sciences are now merging rapidly into one another. The basic principles of chemistry are increasingly finding their explanation in the physical structure of the atom. Similarly, the basic principles of biology are now understood in terms of chemical reactions. These facts have led to some experimentation with courses that present physics and chemistry or chemistry and biology in an integrated way. If such courses are available, by all means take them. If not, the recommended order should in my strong opinion be physics, chemistry, and biology. Physics is often regarded as the hardest, a fact that leads many people to recommend that it be postponed.

It is true that it is the most abstract of the sciences and depends more than any other on an understanding of mathematics. Nevertheless, in schools where good math is available, a well designed physics course can be taken as early as the second year of high school and certainly by the third year.

The recommended order follows the chronological order in which the three subjects developed historically, but this is only a minor reason for recommending that it be followed by today's students. The most important reason is that physics tells us the basic way in which the universe is put together and provides an understanding of the major forces that relate the bits and pieces with one another. Chemistry builds on these principles to give us a picture of more complex material. Finally, biology shows how complex chemical compounds are put together to form life.

The order in which physics and chemistry are taken is perhaps less important than the postponing of biology until after physics and chemistry have been completed. If the latter is not done, there is grave danger that the course will have to be given in a way that actually destroys rather than enlivens the interest of the student. Some students, even some adult biologists, can derive a major satisfaction merely from observing the various forms in which life appears and in classifying them into groups and subgroups—the phyla, genera, families, and species of the classical biologist. This sense of excitement about form and classification is a relatively rare gift and one that was essential for the development of biology in an earlier period. Its great flowering came in the invention and verification of the theory of evolution. So great was its triumph that the study of form and classification has dominated elementary biology ever since. This has meant that the beginning student is confronted by an overwhelming mass of material that can be

mastered only by gigantic feats of memory. Species follow species, each with an awkward new name to be remembered. Furthermore, each species exhibits important variations in the structure of its digestive, circulatory, respiratory, skeletal, glandular, and nervous systems. All these must often be learned before the student has gained much of a notion of what any of these systems does and how it does it. But it is just these latter questions which make the subject interesting to most students. Far too many, however, become so bored with phylogeny that they abandon biology long before they can find out how interesting it can be.

Finally we come to our point. Biological function can be understood only in terms of physics and chemistry. "The heart works like a mechanical pump and develops a pressure as a result of the viscosity of the blood and the resistance imposed by the smaller blood vessels." What meaning can such a statement have to somebody who does not understand elementary hydraulics? "The kidney helps to maintain the osmotic pressure of the blood, as well as the proper pattern of the positive and negative ions, especially the all-important hydrogen ion concentration." What does this mean to someone who has had neither physics nor chemistry? These are only the most elementary sort of examples of the way in which modern biology depends on physics and chemistry. It hardly seems necessary to go any further in defending our recommended order for the science courses.

Nevertheless, one should not be rigid in interpreting the foregoing suggestion. Circumstances do alter cases. Too much advice to students is given in terms of subject content, curriculum design, and so on; too little attention is paid to the quality of the teacher. It is always uncomfortable to draw distinctions between people, and of course it is impossible to do so when the person in question is not known to the person giving the advice. It thus turns out

that much, probably too much, has been written about curricula, textbooks, teaching machines, and movies. Far too little has been written or even thought about the two most important elements in the school situation—the quality of the teachers and the quality of the students. In other words, if you have to change the order of courses in order to get a good teacher, do so by all means. If one or more of the recommended courses is given by a poor teacher and the content is limited to the most unimaginative aspects of the subject, omit it entirely. It is better to take no science in high school than to be turned against science forever by taking a hopelessly bad course.

The previous chapter had something to say about the importance of social sciences; in the next I will discuss the significance of English and foreign languages in the preparation of the scientist. All these subjects should, of course, be begun in high school. Again it will be found that the quality of the courses offered varies enormously from school to school. In many places the social sciences will not be taught as separate disciplines such as history, government, or economics but as a combined course in civics or social studies. There is perhaps nothing wrong with this idea in principle, but in practice it has resulted in a considerable dilution of educational content. In an effort to cover "everything," nothing is treated very thoroughly. The long and often painful history which gives meaning to such important institutions as trial by jury, the right of habeas corpus, or the protection of the Fifth Amendment has tended to disappear. In its place we find a rather bloodless account of how legislatures work or what a mayor does at the present time. Economics is usually so superficially presented as to provide little background for intelligent newspaper reading on such topics as international trade, the role of the Federal Reserve Bank, or the farm problems. Although the dangers

of this situation have been recognized for some time, relatively little has been done about it until very recently. The last year or two have, however, seen some effort to return to more solid courses in history, and a group of distinguished economists are working on a course in their subject which should be appropriate for high school students. If the student is fortunate enough to find himself in a school which offers solid courses in history, government, or economics, he should be advised to elect them instead of the conventional course in civics or social studies. In any case, he would do well to establish as soon as possible the habit of supplementary reading in these fields. Many people have compensated for an inadequate formal education in this way, and no matter how good one's formal education may be, it is never enough.

This may be the place to say something about the formation of what used to be called character. It may seem a little odd to mention this matter as part of becoming a scientist, since so many people seem to regard scientists as disembodied intellectuals. Nevertheless scientists are people and they need to develop certain traits of character in order to perform well both in their private lives and in their professional work. In a later chapter I will have something to say about the relationship of science to morals and to certain other so-called value problems. Suffice it to say here that the pursuit of science itself requires the exercise of certain well known character traits, such as honesty, industry, perseverance, and fair dealing. Furthermore, scientists are increasingly involved in making judgments about the use of scientific power for national defense and the promotion of the general welfare. Decisions whether or not to use a certain drug, a new food additive, or a vaccine require careful balancing of possible dangers against the probable benefits and such judgments cannot be made on

purely scientific grounds. Decisions of this kind, in which the evidence can never be conclusive in a scientific sense, are characteristic of the world of affairs and require among other things such qualities as courage, steadfastness, and an elusive trait known as good judgment which can be acquired only by general experience. Some of this experience can be gained vicariously by reading about how other people have met their problems in the past. In a former time young Americans prepared themselves for responsible living by mastering the Bible and studying the lives of the ancient Greeks and Romans. Most of us have learned in school that Abraham Lincoln studied Plutarch's *Lives* by the firelight in his Kentucky cabin, but we are not much encouraged to read him ourselves. Few of us even remember that Plutarch undertook the preparation of his *Lives* as a comparative study in moral behavior with the deliberate purpose of helping young people to develop better characters.

There is a general feeling today that standards of conduct are deteriorating and that something should be done to improve them. The recent furor over the Supreme Court's decision about praying in the public schools has revealed the intensity of feeling on this matter, but to some of us it seems largely to have missed the point. The development of good character is not primarily a matter of indulging in routine religious exercise. It is not necessarily a matter of religion at all. Plenty of people with good characters belong to no church, and plenty of people with bad ones have been notable for their formal devotions.

Much can be learned about the subject, however, by studying the lives of the figures in the Jewish and the Christian Bible and in the books of other great religions. And there is also much to be gained by knowledge of such secular or even pagan characters as Confucius, Marcus Aurelius, and Agamemnon. Biographical and historical

studies should not, of course, be confined to ancient times. They are emphasized here partly because so many of our basic rules of behavior were developed in those days. It may also be true that the ancients gave more of their time and energy to considering problems of character since they were somewhat less preoccupied with certain technical aspects of living than we are. Whatever the reasons, it is difficult to find any better expression of the problem of the good man confronted by undeserved adversity than the Book of Job, or the troubles of the thoughtful and responsible administrator than the *Meditations* of Marcus Aurelius. Nor have two thousand years added much to what Cicero had to say about the sense of duty.

We do, of course, confront many problems that are unique to our day, and the complexity of our social and economic arrangements makes it harder than ever to plot a true course. Knowledge of recent history and of the lives of outstanding contemporary figures will help in preparing the student to understand the special problems of his own times.

Much of what has been said above applies both to social studies and to literature as presented in courses in English or foreign languages. A special word should be said perhaps to encourage the high school student as he takes up the arduous task of learning how to write acceptable English. As will be discussed more fully in the next chapter, the capacity to write clear and forceful English is an indispensable part of the scientist's equipment. The future scientist should therefore welcome the opportunity to write themes and term papers. If he has a teacher who takes time to make critical comments in the margins, so much the better. It takes long practice to learn to write well and there is no substitute for having someone else point out one's errors, painful though the process may be. In these days of heavy teaching loads, the student who finds a teacher willing to

sit down and do a sentence-by-sentence critique of his written work is fortunate indeed.

It may take some time for a young person to realize that there are enormous differences in the quality of education offered by various institutions in the United States. In other countries, until very recent times, advanced secondary schools and universities have been limited in number, and attendance has been restricted to individuals capable of passing very rigorous examinations. The standards set by some central government body have been roughly comparable throughout the whole country. Generally speaking, a student in a German *Gymnasium* or a French *lycée* followed one of two curricula. One of these concentrated on the classics and modern languages, the other on mathematics and the sciences. In either case, the secondary school graduate emerged with a sound basis of scholarship in his particular field. Everyone knew that he had survived a difficult course of instruction and was well prepared for advanced work. The great majority of pupils never entered the *Gymnasium* or *lycée* at all but were shunted off at about the age of twelve to schools of lower standards which prepared people for nonintellectual activities.

In America the secondary school system developed in quite a different way. Very little, if any, authority was given to the Federal Government to regulate standards. In some areas the state department of education exerts a considerable influence; in others, control of almost every phase of school activity is left in the hands of local boards. All students, whatever their interests, capacities, and future plans, may attend the same school. Only in a few large cities are students allowed to choose high schools particularly suited to their interests and capacities. In other cities the *de facto* arrangement of residential areas by socioeconomic class works out in practice to concentrate the majority of univer-

sity-bound students in one or two high schools. These naturally offer a better opportunity to the future scientist than do the majority of schools in the same town which cater to other interests and capacities.

It is not the purpose of these remarks to imply that the old European system is better than the American. Actually both have their virtues and defects and both are clearly the results of important cultural differences that have grown up on the two continents. The last few years have as a matter of fact seen a healthy effort on both sides to learn more about each other's systems and to combine the best features of both.

The point being made here is that the quality of secondary (and university) education in the United States varies widely from place to place and from school to school. The instruction offered by the Bronx High School of Science, for example, has virtually nothing in common with a rural high school in the deep South except for the names of a few courses.

Not long ago the magazine *Science* published the results of an investigation of the geographical origins of scholars and scientists in the United States. This showed that the New England and Middle Atlantic states produced about four times as many high school graduates per 1,000 who went on to obtain a Ph.D. as did the Southern states. Indeed they outproduced any other section of the country by over 50 percent.[1]

A social phenomenon such as this is of course difficult to explain with any assurance. No doubt many factors are at play, but it seems very likely that at least one of the more important factors is the amount and quality of primary and secondary education available in various areas of the country. This does not mean that all or even a majority of the schools on the East Coast are excellent or that there are

no good schools in the areas with much poorer overall records. What it does mean is that the burden of responsibility placed on the ambitious young American student for planning his own education is *much heavier* than most students realize. If he lives in a part of the country or in a neighborhood in a big city in which he is the only student in 10,000 who has the motivation of becoming a scientist or scholar, the chances are that there will be few people around to help him. His parents and neighbors are likely to have their sights set on other objectives. The guidance counselors he sees in school may be preoccupied with the problems of slow learners or at best with good students whose major motivation lies in nonintellectual directions. More often than not such counselors will fail to recognize the occasional future scholar and to direct him through an appropriate high school curriculum to a proper college or university.

Colleges and universities vary almost as much from one another as do high schools. As Dr. Bernard Berelson has shown in his important study, *Graduate Education in the United States,* there are 175 universities qualified to give one or more Ph.D. degrees. Of these, only 22 give 54 percent of the advanced degrees actually given. These are in fact approximately the same 22 which informed scholars would list as the best universities in the country.

Some years ago Knapp and Greenbaum [2] made an exhaustive study of undergraduate colleges on the basis of the proportion of Ph.D.'s to be found among their alumni. The proportion varied from less than one Ph.D. per 1,000 graduates to 19 Ph.D.'s per 1,000 graduates for the highest on the list. A more recent analysis by Astin [3] shows that most, if not all, of this difference can be attributed to the intentions and capacities of the students who enter the colleges. In other words, there is not much evidence that a certain

kind of college can make scientists out of people who do not have the interest and capacity in the first place. Conversely, a well motivated, intelligent student can go on from almost any college to get a Ph.D. In point of fact, there seems to be no good way of measuring the effects of different sorts of colleges on the students who go through them. Nevertheless, on common-sense grounds it seems obvious enough that a student who is interested in becoming a scientist would do well to go to a place where a relatively high proportion of the students have the same interests and capacities, and the physical facilities and faculty are such as to encourage scholarly work.

To a great degree we do have equal opportunities in this country, but it is undeniable that some young people are in a much better position than others to make the most of the opportunities that do exist. For many centuries inequality of position in society was encouraged or enforced by a combination of tradition, government regulation, and hard economic fact. Much of the progress of the last three hundred years has been made in breaking down the legal and economic barriers to equality. Sometimes this has occurred as a result of bloody revolutions, as in France and Russia. Sometimes it has occurred, as in the English-speaking countries and especially in the United States, as a result of gradual legal evolution. But in spite of undeniable improvements, inequalities still exist.

Many liberals continue to attribute these inequalities to defects in our legal structure and to inequities in the distribution of wealth. Such people seek the solution to the problem of inequality through the political devices that have worked so well in the past: through laws guaranteeing equal rights, through greater provision of scholarship funds, higher minimum wages, and so on. It seems probable that we are reaching the limit of such solutions. Government

can create the environment for equality, but it is strictly limited in its ability to create equality itself. It can and should, for example, see to it that equal educational opportunities for equally capable boys and girls exist, but it cannot ensure that they take advantage of them.

Finally we come to the hard fact that individuals who want to improve their positions, who want, in other words, to take advantage of the opportunities that do exist, must want to do so intensely enough to make the hard choices and do the hard work necessary to develop latent abilities.

How does our system work out in practice in regard to the matters outlined above? Many studies have shown that there is a strong correlation between the socioeconomic status of parents and the amount and quality of education received by their children. This fact is often interpreted purely in terms of money. All that is needed, so runs the argument, is to wipe away the financial barriers and everyone will get the same education. This interpretation is so incomplete that it is probably more wrong than right, although there is certainly still much truth in it.

How then are we to explain the very unequal distribution of academic achievement in the different parts of our society? One of the difficulties with trying to analyze a problem of this sort is that we know so little about many of the factors involved. It is much easier to measure money than cultural outlook, much easier to analyze laws than to assess the social attitudes of individuals. We are still almost completely in the dark in regard to the importance of heredity as a conditioner of academic achievement. On the one hand, we know that parents with high IQ's tend to have children who stand higher than the average. But the IQ is not solely or perhaps even primarily a measure of inborn ability. Many studies have shown that individual IQ's can be markedly improved by exposing a child to an enriched environment.

Perhaps the best evidence we have for basic biological differences in mental ability comes from studies of identical and nonidentical twins. These suggest strongly that there are such differences. From the practical point of view, however, it is much more important for the individual to know that heredity works in such a complicated way that the relationship between the inborn characteristics of a given individual and his brothers and sisters and parents is not particularly close. In other words, very bright individuals are often found in ordinary families. Conversely, very bright parents will on the average have somewhat duller children.

On the basis of present knowledge it seems highly unlikely that either inborn differences or mere financial considerations can account for the major differences in scholastic achievement in different socioeconomic groups. What evidence we have points rather to the fact that the general intellectual level provided in the home makes a great difference in the intellectual achievement of the average child. A child is likely to see more point in learning to read if he sees his parents doing a good deal of reading themselves. The presence of interesting books in the home encourages him to continue to develop his reading ability. A bright child early learns from his parents to look up things in dictionaries, almanacs, and atlases if these intellectual tools lie readily at hand. In other words, his education goes on continuously and is not confined only to a few school hours each day.

Equally, or perhaps more important, is the factor that psychologists refer to as "motivation." Parents who have intellectual interests themselves are far more likely than most other parents to set a high value on intellectual achievement. In many direct and indirect ways they will influence their youngsters to want to do well, and will help

them select a career suitable to their talents. If good schools are not available locally, they may move to another town or send their children to live with a relative. They may even make a considerable sacrifice to send their children to boarding school. All these measures not only result in a superior educational experience; they do something more valuable. They convince the child that education is something important, something worth working for and making significant sacrifices to achieve.

The child who grows up in a home that does not place this sort of emphasis on intellectual matters has a much harder time making use of the opportunities society sets before him. At the very least he must make an effort to get extra help and guidance from his teachers, his pastor, or whatever educated people are available to him. He must learn to use the school and public library instead of expecting his parents to put the right books in his hands. Furthermore, he must learn on his own to compare the kind of schooling he is getting with what is available elsewhere. Finally, he must find out how to select an appropriate college and finance his way through. In many cases he may have to do all this not only without help from his parents but also in the face of their active opposition. The fact of the matter is that many adults have only the vaguest sort of idea about what an intellectual career is like, what its rewards and satisfactions are, and what sort of sacrifices it entails. Until very recently, American culture as a whole has set a lower value on the intellectual life than most other civilized countries do. Scholars, writers, artists, teachers, and scientists have for the most part been underpaid and have often been looked upon as rather oddball and unreliable types. Perhaps it is no wonder that many parents tend to discourage their children from a long, arduous, and

expensive education to prepare themselves for a life of such doubtful blessings.

If all this is true for boys, it is much more so for girls. The cultural pressures both in and out of the home make it very rare for a girl to emerge from adolescence determined on a career in science. School teaching, especially at the lower levels, may be all right, and the arts which almost require that some of their practitioners be women, like acting and dancing, are allowable. Anything requiring intense intellectual effort is out of the question. This attitude is all the more mystifying since there is every reason to suppose that girls are just as bright as boys. Indeed, as a group they routinely get better marks than boys do. Furthermore, the very few who have survived the cultural pressures and gone on into scientific careers have done very well.

We said a little earlier that existing inequalities in this country may no longer be attributed primarily to legal restraints or even to differential distribution of wealth, but must be traced to more subtle cultural factors. No more convincing evidence need be cited than the continued low status of women in the intellectual world. They are now legally fully equal to men; they have roughly the same access to scholarships and student jobs; but they fail to enter intellectual careers in anything except token numbers. The most reasonable explanation for this failure seems to be the low value they have learned to put on intellectual achievement in comparison with other attributes presumed to make them better wives and mothers.

Many recent studies have shown that a modern nation like the United States must recruit sharply increased numbers of its best minds into intellectual work if it is to survive. Fewer than half of the upper 25 percent of all

high school graduates ever earn college degrees.[4] Much of the responsibility for this wastage must rest with society for failing to make the needs and opportunities more widely known, and to help young people get a clear picture of their own talents and potentialities. In the final analysis, however, the responsibility is an individual one. There are definite limits to how much governments can entice or parents can push an individual student into an intellectual career. The student must take the major initiative himself. The responsibility bears heaviest, as we have seen, on the talented youngster who finds himself in a segment of society that habitually knows little or cares less about high intellectual achievement. What can such an individual do?

In the first place, he can discreetly try to evaluate the high school he is going to. It is worth knowing in this connection that large high schools send a much higher proportion of their graduates on to a Ph.D. degree than smaller ones do, especially in the sciences. High schools graduating from one to 20 students per year produce future Ph.D.'s in the physical sciences at a rate of only 0.69 per 1,000. From there the rate rises steadily until it reaches 7.3 for schools with classes of over 800. But size alone would be an uncertain criterion. There are several other ways the student can judge the quality of the schools available to him.[5] For example, he can, without too much difficulty, find out how many recent graduates have been admitted to good colleges. The Knapp and Greenbaum book will be helpful at this point and later on in evaluating the intellectual level of the colleges concerned. He can also determine whether a school is participating in the widespread effort to improve secondary education. Is it experimenting with one of the new mathematics programs; has the PSSC physics course or one of the new chemistry courses been introduced? Have some of

his teachers attended the summer institutes sponsored by the National Science Foundation? Does the school offer three or four years of instruction in at least one modern foreign language with a teacher who can speak the language at least fairly well? Does mathematics extend at least through trigonometry and logarithms? If the answers to most of these questions are in the affirmative, he is probably safe in staying where he is. If, in addition, there are advanced courses in mathematics—college algebra and elementary calculus, for example—and some of the graduates enjoy "advanced placement" in other subjects when they reach college, he is really in luck.

If, on the other hand, relatively few graduates go on to any college at all, only an occasional one gets to a good university, and there are few symptoms of progress in improving the curriculum or the quality of the teaching staff, the ambitious student is in for a tough time. It is, of course, possible for an outstanding student to overcome the handicap of indifferent schooling and finally end up in a good graduate school. The real genius seems to be able to overcome any environmental handicaps and come out the better for it. But such people are very rare. The great majority of us need all the help we can get from teachers, parents, and fellow students if we are going to realize our potentialities.

Once the student has come to the conclusion that he is not the sort of genius who can educate himself and that the school he is going to will not help him to get into a good college, he must tactfully begin to explore alternatives. He should take a look at the other schools in his city or in nearby towns. If one of these turns out to have the desirable characteristics we have described, he can look into the legal and financial problems involved in transferring. Some cities like New York and Boston make it very

easy for qualified boys and girls to attend schools which are primarily designed for college preparation. Others make it very difficult. Sometimes the best solution for the ambitious student is to go to live with a relative in another school district. If such a relative doesn't exist, the student may be able to arrange room and board with a reliable family in return for doing odd jobs and chores around the house. One or another of these patterns was, as a matter of fact, the *usual* way for a bright boy or girl to get a good education a generation or two ago before high schools of any sort were as widely distributed as they are now.

Finally, there is the possibility of attending a good boarding school. The opportunities in this direction may be a good deal brighter, especially for boys, than most people imagine. To most Americans the private boarding school is likely to seem remote from the reality of everyday life, snobbishly available only to the children of the very rich. It must be admitted that there is some truth in this, especially as it applies to the "name" schools in the Northeast and a few on the West Coast. Much more commonly than is recognized, however, even these name schools are anxious to help promising young boys with limited financial resources. Not only do they feel a responsibility to make their excellent facilities available to those who can use them most effectively, but they are often as aware as their critics of the dangers of limiting their enrollments to rich and fashionable families. Such schools as Exeter and Andover, for example, have always prided themselves on their democratic outlook. Over the years they have accumulated substantial scholarship funds to meet at least an important part of the expenses of students unable to pay their own way. Several of these schools send admissions officers on extensive trips throughout the country in a special effort to find exceptional boys whose needs are

not being met by local public schools. Some of the larger religious denominations also sponsor good boarding schools and it should be well worthwhile to discuss the possibilities with one's minister or priest or rabbi. It must be recognized, however, that secular and religious schools vary almost as much in quality as do public high schools, and the prospective student should be prepared to ask the same sort of questions and to take the same sort of responsibility for making up his own mind in both cases.[6] All we wish to emphasize here is the probability that it is a good deal easier for a really bright and ambitious boy with limited means to get a hearing from a good private boarding school than most people think.

There are many things one can do outside of formal school hours to help in becoming a scientist. Extracurricular school activities, hobbies, and certain sorts of jobs offer many opportunities for meeting professional scientists and acquainting oneself with what science is all about. One of the best organized of the hobby activities is ham radio. Many high schools have clubs that offer an easy way of getting into this activity. If not, there is almost sure to be an amateur operator in the neighborhood who will be glad to introduce the newcomer to the mysteries. Although ham radio is principally concerned with applied science, it does provide an interesting and pleasant way of learning a good deal about basic electronic theory.

The science contests that have grown up in recent years have stimulated a wide range of activities on the part of high school students, some of which have reached surprisingly advanced levels. Even hot-rodding has its scientific aspects and at the very least provides an opportunity for mastering machine shop techniques and principles which will be useful in the laboratory later on in life.

The enterprising high school student should be encour-

aged to look for opportunities to work after school and during vacations in whatever research laboratories may be available nearby. Individual scientists vary a great deal in their willingness to initiate young people into the scientific way of life, but some, at least, are very eager to help. I know of one laboratory in New York, for example, which regularly offers opportunities to high school students to work on advanced problems of biological research over weekends and during vacations. Several of them have had the satisfaction of seeing their names on scientific papers before they entered college. More often, the student will have to begin at the humble level of glassware washer or animal attendant, but if he shows himself interested and reliable, he may quickly graduate to the status of technical assistant and begin learning basic experimental techniques. In any case, he should profit from the atmosphere of a laboratory where actual creative work is going on, an atmosphere very difficult to approach in most teaching laboratories in secondary schools.

Last but not least, some mention should be made of outside reading. One's science teachers and the high school librarian will in most cases be glad to guide the student to books which will enlarge his grasp of science itself and improve his understanding of what it is like to be a scientist. For example, a set of excellent monographs on particular aspects of physics is being made available in connection with the PSSC physics course. Some classical works of science can be read in their original form by advanced high school students and fortunately the best of them are often available in paperbook form. Darwin's *Zoology of the Voyage of H.M.S. Beagle* and *On the Origin of Species by Means of Natural Selection* have served as an introduction to biology for many people for just over 100 years. William Harvey's description of the circulation

of the blood, published in 1628, requires little technical background and serves as an excellent introduction to the experimental method in biology. Broadly speaking, the original early work in physics and chemistry is more difficult to read than that in biology. Not only is a knowledge of mathematics required, but the form in which the mathematics is presented is often awkward and unfamiliar to present-day students. Nevertheless, much of Galileo's *Dialogues Concerning Two New Sciences* can be read quite easily to give some insight into how he went about revolutionizing physics and the fun he had in doing it.

The world of science is not as well provided with biographies as is the world of politics and military affairs. Nevertheless, good biographies do exist for certain key figures like Newton, Darwin, and Pasteur, and many others will be found somewhat unevenly distributed over the field. They provide a pleasant way of learning the more human side of science often omitted from the textbooks—the hard work of observation, the excitement of the new idea, and sometimes unhappily the bitter and unseemly arguments with proponents of rival theories.

Finally, we should all rejoice over the existence of *Scientific American*, *Science News Letter*, and the most recent publication, *Science and Technology*, each devoting itself to a somewhat different aspect of science, but each excellent in its own way.

Notes

[1] Lindsey R. Harmon, "High School Backgrounds of Science Doctorates," *Science*, V, 133, 679–688, March 10, 1961.

[2] Robert H. Knapp and Joseph J. Greenbaum, *The Younger American Scholar: His Collegiate Origins*, Chicago, University of Chicago Press, 1953.

[3] A. W. Astin, "Productivity of Undergraduate Institutions," *Science,* V, 136, 129–135, April 13, 1962.

[4] *America's Resources of Specialized Talent: A Current Appraisal and a Look Ahead,* The Report of the Commission on Human Resources and Advanced Training, prepared by Dael Wolfle, Director, Harper, 1954.

[5] Lindsey R. Harmon, "High School Backgrounds of Science Doctorates," *Science,* V, 133, 679–688, March 10, 1961.

[6] A good guide to follow is *The Handbook of Private Schools—An Annual Descriptive Study of Independent Education,* 43d Ed., by F. Porter Sargent, Boston, F. Porter Sargent, 1962.

8

College

THE COLLEGES IN THIS COUNTRY VARY FROM ONE another in quality to almost the same extent as do the high schools. This variation is perhaps particularly marked in relation to the training offered in the sciences, since good work in the sciences requires more substantial outlays for teaching and research equipment and often for teachers' salaries than is usual in other fields. Although it will make life much easier for the future scientist if he goes to a good high school, there are plenty of people who have survived an indifferent or even poor experience at this level and gone on to very successful careers. It is much harder, though still possible to do so, if one fails to get a clear idea of what science is all about in college. Most future scientists must make their final career choices at about this stage. During this period, therefore, they should not only lay a solid groundwork of scientific information and habits of thought, they should also gain a clear idea of what it is like to be a scientist.

Far and away the best way of doing this is to observe real live scientists at work and to participate in some research oneself. It is the opportunity to do just this that good colleges offer their students. Poor colleges do not. Clearly the student should give careful attention to the selection of a college. In choosing a specific institution he

will, of course, be helped by his teachers and guidance counselors, by his parents, and finally by friends who have recently attended the institutions he has in mind.

All that can be done here is to discuss a few general principles. In the first place the American student will have to choose between going to an independent liberal arts college or to a college associated with a university. No general rule can be laid down that will hold for every case. Matters of personal taste or family tradition may properly be allowed to play a considerable role. In a theoretical statistical sense, the probability of getting a good science education is higher in a university than in an independent liberal arts college. This is true simply because all universities must have at least some research going on while many liberal arts colleges have little or none. On the other hand, there are at least twenty and perhaps as many as fifty liberal arts colleges which offer a better introductory experience in science than do any but a handful of universities. The Knapp and Greenbaum study referred to in the last chapter shows, in fact, that the best independent liberal arts colleges send a far larger proportion of their graduates on to advanced degrees in science than do the colleges attached to universities. Some of the differences between the two sorts of institutions may be worth bearing in mind when making a choice.

The best liberal arts colleges may not have as elaborate laboratories as the best universities and they usually lack the relatively small number of absolutely outstanding scientists that give the best universities their reputations. However, the best college laboratories are fully adequate for undergraduate work and provide research facilities good enough to attract perfectly capable if not absolutely outstanding teachers. The introductory science courses in the independent colleges have fewer students and almost all

the teachers are experienced and interested in teaching. The same courses in universities must deal with many more students. The big-name teachers typically confine themselves to the research laboratory and to teaching advanced workers. The beginning student is dealt with more often than not by inexperienced graduate students whose principal preoccupation is with their own efforts to get Ph.D. degrees. The recent growth in scholarship aid for graduate students has unfortunately had a deteriorating effect on the teaching of undergraduates. In the old days the best graduate students worked their way through school as teaching assistants. Now they hold full scholarships which allow them to devote full time to study and research. In too many instances this means that only the poorer students apply for the teaching posts.

By junior year the probable superiority of the independent college begins to disappear and the honors student may in fact be somewhat better off in the university than in the average good small college. This is especially true if he has by that time developed an interest in one of the subspecialties of science. Most small colleges limit their scientific departments to the major scientific fields and do not cater to students with special interests, for example, in anthropology, geology, or the various branches of physics and chemistry that require expensive specialized apparatus. An increasing number of universities is making provision for accepting transfer students at the junior year so as to provide for liberal arts college people who develop special interests of this character.

Although I believe the above comparison of colleges and universities to be substantially correct in a general sense, there are many other considerations which may properly enter into the student's choice. Much will depend on the individual's personal tastes and his ability to make

the most of the advantages and to minimize the disadvantages inherent in the institution he attends. It must always be remembered that our best universities and our best colleges offer much more than even the best student can absorb.

I will have relatively little to say about the choice of particular courses. All colleges have certain requirements for concentrating or majoring in one field and for broadening one's experience through contacts with other subjects. A corps of deans and advisers will be at hand to help the student arrive at choices suitable to his needs. The science courses chosen will depend upon how soon one is able to arrive at a decision about a field of specialization within the broad field of science itself. By and large, it is probably wise not to specialize too soon but to continue one's contact with the basic fields of physics, chemistry, and biology at least through sophomore year.

The first reason for concentrating on basic science before entering one of the specialties is a theoretical one, but none the less important. As we have said before, science is an effort to explain things in terms of other things. It appears to us now that the simplest and at the same time most comprehensive terms of explanation are the terms of physics and chemistry. To put the matter in its baldest terms, the oceanographer, the meteorologist, yes, even the psychologist who doesn't know physics and chemistry, simply doesn't know the language in which his most important statements are going to be made. It can be admitted that there are today numbers of workers in all these fields whose knowledge of physics and chemistry is pretty rudimentary. By virtue of long experience or natural ingenuity they can identify and define certain gross aspects of their field of study and so lay the ground-

work for asking more precise questions, but more and more rarely will they be able to suggest the answers.

A more immediately practical point is raised by the fact that almost all fields of science now employ methods of observation which are basically physical or chemical in nature. The oceanographer, for example, sets off an explosive charge and traces the sound as it is reflected or refracted by the water of the ocean and of the several layers of rock underlying it. The instruments he uses to make his observations and the formulas he employs in interpreting the results are both dependent for their effectiveness on a sound knowledge of basic physical principles. Highly refined chemical methods for separating and identifying isotopes give him additional data on the age of the water in various layers of the sea and thus reveal the nature of vertical as well as horizontal ocean currents. Similarly, the modern psychologist uses the most advanced sorts of electronic apparatus to record the electrical activity of the brain during the performance of such classical psychological phenomena as sensation, perception, and learning. If he is a very modern psychologist, he may even attempt to interpret the results with formulas derived from study of the passage of electrical impulses through randomly arranged electronic networks. Already such terms as "positive and negative feedback" and "self-correcting, goal-directed activity," derived from the study of physical servo systems, have served to guide the hand and brain of the psychologist as he tries to dissect the tangled wires that connect the brain with the mind.

A third reason for deferring the choice of a scientific specialty until one has had considerable experience with the basic triad has to do with the sort of evidence one needs in order to make a choice. No matter how much

one reads about science or talks with people who are engaged in scientific work, one really cannot imagine how it feels to be a scientist until one experiences it for oneself. It is therefore important to preserve as long as possible the opportunity to try oneself out in a variety of scientific experiences before making a final choice. The basic sciences are the most general in outlook and provide the widest sort of experience in themselves. Furthermore, a knowledge of physics, chemistry, and biology opens the doors to experience in the more specialized subjects. For example, a college student with such knowledge stands a much better chance of a summer job on an oceanographic ship or in many psychology labs than one without such knowledge.

In this connection it may be well to warn the student against some of the trivial temptations that still exist in college curricula as remnants of the free elective system. During most of this century it has been customary for the colleges in this country to require their students to take a certain number of courses in a major field of concentration. In the hope of ensuring breadth of experience, the student is also required to distribute his interests among certain other fields of knowledge. Thus, those who concentrate or major in the sciences must take one course in history, one in literature, and perhaps one in the fine arts. Conversely, majors in the humanities are required to have one course in science. Noble in motive though this requirement may be, the practical results have been generally unsatisfactory. It is no secret that most of the introductory courses in the classical subjects of physics, chemistry, and biology are regarded my most students as both hard and dry. Not unnaturally they look around for something to fulfill their "science requirement," which will be easy or amusing, or if possible—both easy and amusing.

For many years geology met these specifications very well in some colleges. For one thing, it turned out that the elementary courses could be taught quite well without requiring a prior knowledge of mathematics. Certain famous teachers also found ways of embellishing the course with general observations on time and evolution and a variety of other topics. If, in spite of this, symptoms of boredom appeared in the classes, a field trip to a nearby mountain, ravine, or seashore could be arranged.

Physical anthropology similarly capitalized on the skill of distinguished professors in imitating the stance and habits of the great apes while cultural anthropology made much of the fancied delights of coming of age in Samoa. Charming as these interludes were, they did very little to acquaint students with what science really is or to attract them into scientific careers. Worst of all, they failed almost completely to indicate the important place that science occupies in modern society.

Even though one should seek to develop a firm grasp of the basic sciences during college, it is important not to fall into the trap of devoting oneself exclusively to science at this stage. The future scientist is also a human being and a future citizen. In order to function well in all three capacities, he needs to know as much as he can about other approaches to the problem of living. Since many people tend to be attracted to science partly because they may have found themselves less effective in high school courses in language, literature, and history, it may be necessary to say a special word about the importance of these subjects. At the start of one's scientific career it is easy to overlook the fact that the successful scientist depends heavily on a skillful use of language to communicate his results to other people.

As we found in Chapter 2, science is essentially a way

of describing the nature of things in ways that other people can verify. In a very practical sense, a scientific statement is simply not important unless other scientists can understand what it says and what the evidence for it may be. The operations for obtaining such evidence must be described sufficiently clearly to enable others to repeat the original observations as quickly and easily as possible. In practice such descriptions are published in the form of scientific papers in the numerous journals established for this purpose. The average scientist may prepare some five to ten papers each year. Ordinarily he gives a number of formal and informal talks to groups of his colleagues as well.

Experience shows that the great majority of beginning scientists have a great deal of difficulty expressing themselves clearly and gracefully either in writing or orally. Much time must be taken from laboratory work to learn the art of communication under the guidance of the senior scientists he is working with. It is not uncommon for a graduate student's early papers to go through as many as ten drafts before being sent off to the press. Even then the task is often not completed. Far too many papers must be sent back by the editors for further condensation and polishing. All this is extremely time-consuming and frustrating. All too often the painful process results in an emotional block against writing papers at all. Far too many otherwise productive workers keep postponing the unhappy task while they continue to pile up masses of poorly organized data. This is bad for their personal careers and equally bad for the progress of science. Much of this waste could be avoided if more future scientists would prepare themselves with verbal skills during their school and college years.

What shall we say about foreign languages? The tradi-

tional theory has been that scholars should have a command of at least two languages other than their own. As a matter of fact, most European scholars have always been able to speak at least one and ordinarily two foreign languages. Even if their conversational ability was a bit shaky, they could almost certainly read English, French, and German easily and puzzle out two or three other Latin languages.

Unhappily the same cannot be said of Americans. Before the growth of American universities toward the end of the last century, the situation was in a way better than it is now. Anyone wanting to do advanced work in a scholarly field or a practical art like medicine had to study abroad. Furthermore, a large proportion of the world's scholarship was at that time published in either German or French. The result was that most American scholars were in those days able to read both languages and could ordinarily follow a lecture or conversation.

As graduate training became available at home and more and more work came to be published in English, the incentive to learn other languages declined and American intellectuals became more and more provincial in outlook. Their attitude reminds one of the old Boston lady who is alleged to have asked, "Why should I travel when I am already here?" In many, perhaps most, universities there is still a requirement that graduate students demonstrate a reading knowledge of two foreign languages before obtaining the Ph.D. It must be admitted, however, that in practice this requirement has been very loosely administered—so loosely, in fact, that the majority of graduate students today do not really have a useful ability in languages other than English.

It is true that a much higher proportion of the world's scientific work than ever before is now published in Eng-

lish. A growing fraction is, however, coming out in Russian and there is still a great deal of important work that first sees the light of day in German or one of the Romance languages. Many earlier studies which still have current importance have never appeared in English. These facts alone should be enough to stimulate the future scientist to a facility in at least two other languages. But there are other, perhaps more persuasive, reasons.

In a future chapter, I shall discuss the role of the scientist as an internationalist. Science is one of the most forceful instruments for bringing people together and for enlarging areas of agreement. Increasingly the American scientist is being brought face to face with his colleagues in other lands. In these personal encounters it is most embarrassing and in a way discourteous to have to insist on English as the medium of exchange. The American is also seriously hindered in taking an active part in conferences and seminars in which the participants are more or less assumed to know two or three languages. Even the most versatile linguists among foreign scientists are likely to find it much easier to express new or half-formulated ideas in their mother tongue. The American who cannot follow is thus cut off from the most interesting part of the conversation, and his own investigations may fall behind the parade as a result.

Finally, many American scientists are feeling an increasing responsibility for the development of science in the new countries. Many of these developing areas use languages other than English—French, Portuguese, and Spanish being the most common. The American who does not know at least one of these is virtually barred from participating in one of the most challenging opportunities offered to scientists of the present generation.

Growing recognition of the need for Americans to ac-

quire oral facility in languages has led to the development of new and far more efficient methods of language learning. Some colleges have instituted these in the regular curricula; others offer special intensive summer courses. The future scientist would do well to look into the availability of such courses in his neighborhood. Often an intensive summer course followed by a summer abroad will produce the necessary results while leaving the regular college year free for other interests.

In any case, the future scientist should not be misled by the deplorable tendency of many graduate schools to loosen up on the language requirement. The members of the committees who make these decisions have undoubtedly been overinfluenced by the growing use of English in formal scientific communications and by their own guilt and embarrassment at being poor in languages themselves.

Space does not permit a prolonged and elaborate defense of the so-called "humanities" as part of a scientist's education. Detailed analyses will be found elsewhere. Let me merely state my general agreement with the thesis promoted by C. P. Snow [1] that the well-being of our society, perhaps its very existence, depends on a marked increase in understanding and interchange among representatives of what he calls the two "cultures." As he illustrates, it is a matter of some pride to many scientists to know rather more about the humanities than the humanities people know about science. This tradition deserves to be cherished and encouraged.

The case for the humanities rests not only on their undoubted contribution to a richer, fuller, more understanding personal life. As I will try to show in later chapters, the scientist is increasingly called upon to play a part in matters of high policy and in what are often referred to as "value problems." He is simply unqualified for such

participation unless he has some cultivated sensitivity to the hopes and fears, joys and tragedies, dogmas and ironies, morality and wickedness through which and by which men have guided their lives since history began.

Notes

[1] *Two Cultures and the Scientific Revolution* by C. P. Snow, New York, Cambridge University Press, 1959.

9

Graduate School

THE NORMAL AND NOW JUST ABOUT THE UNIVERSAL WAY to qualify as a professional scientist is to procure an advanced degree from a graduate school. Ordinarily this degree will be a Ph.D. or a doctorate in science. Some biological scientists attend medical school and become doctors of medicine, but they will ordinarily need to do two or three additional years in postgraduate research before being recognized as fully qualified scientists. Some of them will use these two or three extra years to pile a Ph.D. on top of an M.D.; others will not worry about this additional formality.

It is a little sad that becoming a scientist is now so regimented. In a way it would be much nicer if any reasonably intelligent and curious person could gain recognition for carefully performed observations bearing on some question of significance. As we have seen, science actually developed largely as an avocation pursued by people who actually supported themselves in other ways. It is still possible for the talented amateur to contribute to science and a certain number still do. An occasional new species of birds may be named for an amateur bird watcher, and there is quite a large group organized to provide coordinated observations on bird migration. There is also a society of amateur astronomers which has been very helpful

in filling out the map of the heavens. By and large, however, modern science requires so much expensive apparatus, so much technical assistance, and such intense application to keep up with the rapidly moving frontier of knowledge, that the overwhelming majority of contributors must work as parts of large organizations. Organizations necessarily tend to build up sets of rules and regulations, and one of the rules for admission into a full-fledged participation in science is an advanced degree. This regulation is not really so arbitrary as it may sound, since in fact it now requires considerable experience to equip one for independent work in most branches of modern science. For one thing, it takes several years even to get a clear idea of what already has been done in one's chosen specialty. Equally important is the mastering of observational techniques. As I have pointed out before, science progresses by developing more and more refined ways of looking at things, and it takes a lot of time and effort to learn the manipulations involved and to develop the judgment necessary for interpreting the results.

A person who for one reason or another cannot enter graduate school immediately after college, or even go to college immediately after high school, need not be discouraged about the possibility of doing scientific work and becoming a respected member of the scientific community. As pointed out in Chapter 5, a great many people are employed in nonprofessional positions in scientific laboratories. Even though they rarely reach the stage of designing their own experimental program *in toto*, they often find opportunities to contribute to the improvement of techniques and the refinement of details. They thus have a sense of participating in the creative spirit which is characteristic of all good laboratories. In any case, a good technician can always win the respect of his colleagues both above and below him on the laboratory team by his mastery of

the various crafts that are an essential element in scientific work. Indeed, as the senior scientists become more and more involved with the overall direction of the laboratory program, with supervising graduate students, and with serving on the innumerable committees which now form such a prominent feature of the scientific world, it is frequently the junior staff members and the technicians who command the greatest skill in the essential observational phase of the scientific process. This fact not only gains the respect of their colleagues but places the technician in the strategic spot for noticing those chance occurrences which often lead to the most novel and challenging discoveries.

Even if they don't have the flair for original observation, many technicians derive a major satisfaction from working with a team of unusually interesting people in an atmosphere somewhat less formal and regimented than is commonly found in commerce and industry. All these considerations make a scientific job well worth looking into, even if one feels that he lacks the intellectual capacity or ambition or financial backing to reach full-fledged professional status. Currently many girls find a technician's job a satisfactory compromise between their wish for some sort of a career and the equally important drive to become a competent wife and mother.

Finally, the position of technician provides a good transition stage for those who for one reason or another are not quite sure that they want to go on to full-fledged status. Often a year or two in a laboratory will uncover hitherto unexpected abilities and interests. With the encouragement and sponsorship of a perceptive boss, the temporary technician may be stimulated to take the plunge into graduate school. In this connection it is well to remember the practical point that technicians are reasonably well paid and, if they have no outside obligations, can often save enough

in one or two years to pay the expenses of a first year in graduate school.

For the college graduate who has already decided to become a full-fledged professional as soon as possible, the need for an additional three to five years of formal or at least semiformal education may look rather depressing. The situation is not, however, nearly so bad as it sounds. In actual fact, many people look back on their time in graduate school as among the best years of their lives.

Depending in part on the amount of related work accomplished in college, there will be a certain number of formal courses to be taken in graduate school. On the whole, these will be more interesting and more maturely presented and will offer more exciting challenges to the student than the undergraduate courses he has taken. Many will be in the form of seminars offering a good deal of personal discussion with other students and with some of the best members of the faculty. Much more scope will be offered to the student's originality and much less emphasis will be placed on routine requirements. Often a graduate seminar course will merge imperceptibly with an opportunity for independent research.

The number of required courses will vary with the school, with the student's previous experience, and with his field of specialization. In most places, at least one full year of course work will be necessary, followed by additional seminar courses in succeeding years. Toward the end of the second year (in most schools the time is rather flexible) the student must demonstrate a grasp of the basic knowledge in the particular field he has elected by passing a so-called "general examination." This is ordinarily oral in form and it is either a very brave or a very indifferent student who can go through the experience without a qualm. One can indeed feel rather lonely sitting across the

table from four or five prominent scholars, each one apparently bent on demonstrating how much less you know than he knows about a particular branch of knowledge. Nowadays, this picture of the general examination has become somewhat of an illusion. The amount of knowledge in even a highly specialized field is now so vast that everyone recognizes that the aspiring graduate student cannot know it all. More often than not, therefore, the examiners try to act like friendly fellows who are trying to make sure that the student knows enough of his general field to justify his beginning to specialize in a single problem.

If the student has not followed the recommendation to master a foreign language or two in school or college, he will need to devote some time to meeting the language requirement at this later stage, otherwise the last two or three years of graduate school are almost wholly devoted to carrying out research. Increasingly the problem on which he works will be related to the ongoing research program of the department in which he is studying. In the most unfavorable case the student may function primarily as a technician accumulating data to fill out some design laid down by the department head. In practice, however, very few research programs can be so completely outlined in advance that their carrying out becomes nothing but routine. Almost always something unexpected turns up to catch the attention of the alert investigator. Often such unexpected events provide the leads into a wholly new line of research. A good research supervisor will encourage his graduate students to follow up such leads on their own. In any case, sooner or later the graduate student will begin to encounter the joys (and the disappointments) of personal investigation.

Sometime during his graduate training, if not earlier, he will publish his first paper and have the indescribable

satisfaction of seeing his own work and his own name in print. As we have seen, most graduate students will have gone through a massive struggle in putting their first efforts into publishable form. This effort will be more than amply repaid, however, when the first requests for reprints from distinguished investigators begin to come in. A little later on, the student's heart will beat a bit faster when someone refers to the interesting and challenging results, or the unusually beautiful preparations, of Mr. Liebarbeit and his collaborators. He may have to wait a bit longer for epithets such as "masterly analysis," and he may only dimly descry the day when someone will be kind enough to refer to Liebarbeit's "classical studies." Few graduate students, however, allow themselves to imagine that their work may ultimately emerge as a "monumental monograph."

But Mr. Liebarbeit does not have to depend on these nebulous future satisfactions. He is in all probability having a lot of fun already. Very probably for the first time in his life he is surrounded by people who are just as bright or brighter than he is and who have the same sort of interests. He doesn't have to be embarrassed by his lack of interest in athletics, his awkwardness on the dance floor, or his ineptitude at the lighter side of teen-age social life. He is valued for what he is and not looked down upon for what he is not. Much of his time is spent in talking with other graduate students and his seniors in the department about the conduct of investigations in which all are interested. Some of this occurs in formal seminars, but increasingly it will occupy the coffee break and the laboratory lunch hour to which everyone brings his own sandwiches. To the irritation of the nonscientific spouse, dinner engagements are likely to turn into informal seminars too.

Very soon his circle widens to include workers in the same field in other universities and institutes throughout

the country, and he may begin to exchange letters with colleagues on other continents. Toward the end of his graduate years he may well get a grant to enable him to attend an international conference where he will meet his overseas friends previously known only through correspondence or by their published papers. If he has managed by this time to have contributed some significant new detail to the pool of knowledge or, perhaps better yet, developed a new technique for seeing something nobody has seen before, people will flock around him at such meetings to get the word on the most recent improvement. Although science has its hierarchy of assistant, instructor, assistant professor, professor, and departmental chairman, its gold medals, Nobel Prizes, and even knighthoods, the graduate student who has done something worth hearing about is immediately accepted into this society as a social equal. Any one of the aforementioned big shots may drop into his lab to find out just how he puts his electrodes into a particular cell or prepares his ion exchange resin to absorb a particular peptide.

Nothing in life is perfect, of course, and there is at least one very uncomfortable feature to the graduate program. Traditionally the graduate student must demonstrate his capacity for pursuing original work by writing a thesis. Again traditionally, the thesis consists of a more or less comprehensive review of the literature bearing on the subject of the student's choice plus a section dealing with his own investigations. In an earlier time the completed thesis became the subject of a public discussion or "defense" by the student against the questions raised by a designated group of his elders and betters. More or less the whole community turned out and the participants were all dressed in formal academic regalia and comported themselves with great formality. If this ordeal was success-

fully passed, the new doctor gave a dinner for his professor which frequently exceeded the student's capacity to pay without going seriously into debt. Usually he went further into debt fulfilling the requirement that the thesis be published in printed form.

The color, excitement, and expense of the occasion have been greatly reduced in the present age of quantity production of Ph.D.'s, more democratic customs, and matter-of-fact approach to life in general. The examination on the thesis is still the climactic event of the graduate course, but it is generally held behind closed doors. The attitude of the examiners is on the whole friendly and directed at finding out what the student knows rather than at tripping him up on some obscure detail. Nevertheless it is a trying experience for many students and there has been a deplorable tendency to postpone the evil day by spinning out the writing of the thesis.

Theoretically graduate training is supposed to extend over a three- or four-year period, but the termination is very flexible and depends entirely on when the thesis gets done. I don't know what the longest time ever taken to write a thesis has been, but I have personally known people who have consumed more than ten years in the process. Everyone, of course, wants his thesis to be outstanding. Aside from the natural desire to do a good job, there is the practical point that one's reputation among his colleagues, the kind of job one gets, indeed one's whole future career depends rather critically on the quality of one's thesis. There are a number of difficulties involved in producing a really satisfactory result. In the first place one must choose a question to work on which is neither so obscure and difficult that the outcome is quite uncertain, nor so obvious and routine that it can hardly be classified as original work. It may in fact be quite hard to arrive at

this happy medium, and many students consume months or years in exploring possible leads before the final choice is made. If one is diligent, capable (and to a certain extent lucky), some two years after settling down with a good topic one will have reached a fairly obvious stopping point. The literature will have been well canvassed, a number of good experiments completed, and some sort of conclusion reached about the nature of this or that bit of the universe.

Unhappily, more often than not things will not have progressed so well. Some of the barriers to rapid thesis writing are to be found with the process itself, others are concerned with the external life of the thesis writer. In the first place, the techniques originally planned turn out not to have the accuracy required for differentiating between two alternative answers to the original question. Time must be taken out to devise new ones. Unforeseen delays occur in the delivery of apparatus. A colleague who was going to do the chemical analyses gets sick or accepts a job somewhere else. Even if these preliminary setbacks do not occur, it is more than likely that somewhere in the course of the experimental program results will be obtained which suggest an explanation that neither the student nor his sponsor had thought of.

Any one of these contingencies naturally has a tendency to delay completion of the thesis. If the delay can be kept to not more than a year or two, everyone remains quite happy and the situation is regarded as normal. As time wears on, however, more and more questions are likely to be asked by the writer's friends and relatives and especially by his sponsors in the department. This tends to react badly on the writer, who becomes increasingly self-conscious and uncertain. These feelings tend to make him less efficient than before and a kind of anticompletion vicious circle is set up. Finally, in the worst cases, the writer becomes aware

that he is taking an undue amount of time and decides that the only way he can justify this excessive consumption is to produce a really monumental piece of work. Since it is given to very few graduate students to produce monumental thoughts, a policy based on such a possibility is usually bound for disaster.

Fortunately, most graduate students do manage to disentangle themselves from these downward spirals and in a median span of some eight years [1] after graduating from college finally get their Ph.D.'s. This figure has the advantage of being relatively precise, since official records of the time of taking degrees are well kept. It is, however, inaccurate in the sense that it includes a good deal of time spent in other ways than in actual studying for the advanced degree. Estimates of the time spent in actual study give the much more encouraging figure of approximately 3.2 years. Nevertheless, there is a growing feeling, especially perhaps among natural scientists, that the whole business is somewhat of an anachronism. The general structure of the thesis, as we have seen, comes down to us from medieval times when scholarship served a set of purposes rather different from those that obtain today. The stated purpose of the thesis is the demonstration of the ability to do original work. Under present conditions this ability is more appropriately demonstrated by the publication of short, clear accounts of specific observations directed at establishing some well defined item in the constantly growing body of knowledge. This sort of paper is in fact the typical product of most working scientists most of the time. After they have gained some experience and stature in a particular field, they may be asked to prepare a more comprehensive review article which is somewhat more like the traditional thesis in form. Occasionally a man who has long been identified with a particular body of knowledge

and who has the rather specialized tastes and talents for the task may write a monograph or even a treatise on a given topic. Many very competent scientists never reach this stage, however, and it seems rather silly to require that candidates for the profession of scientist demonstrate the ability to write in monographic form.

As Dr. Bernard Berelson has shown in his very valuable account of the current state of graduate education in the United States, the foregoing considerations have provoked serious thought on the part of responsible educators. It looks now as if the next few years would bring a considerable streamlining of the whole process of graduate education in which a drastic modernization of the thesis requirement would play a key role. So far, we have said very little about the choice of a particular graduate school. Actually it is difficult to give very much general advice on this subject since so much depends on the subject of particular interest to the student. As pointed out above, over half the graduate students in the country will be found in but twenty-two universities. Very few, if any, of these will be equally good in all subjects. Conversely, certain schools not included in the top group will offer first-class opportunities in one or more special areas. In many fields the presence of one distinguished teacher is enough to determine the student's choice. Since teachers shift about a good bit, and the importance and attraction of particular subject areas change rather rapidly, most students will have to base their choices on what they can find out from friends and college teachers at the time they must make a decision.

In most fields, a small number of universities (perhaps three to six or seven) will appear to stand clearly above the others. Competition for places in such schools will be high and admission limited to candidates who have stood well up in their college classes. All is not lost, however,

if preoccupation with other matters in college or lack of a genius level IQ has kept one from the high honor group. Such a person may have to enter a somewhat less celebrated graduate school, but in most of the first twenty he will find very competent teachers and excellent physical facilities. Finally, we come to the reassuring fact that although competition for the best places is admittedly stiff, no one who really wants to go to graduate school will fail to find a place somewhere.

We should now say a few comforting words about the costs of graduate education and the ways these may be met. Prospective students and their parents are likely to be somewhat frightened by the prospect of three to five years of what looks like financial dependency beyond the level of the college degree. These worries are now more obsolete than the thesis requirement. They stem from the fine old days in which individuals and their families were supposed to shoulder the responsibility for the costs of education themselves. In fact it was even thought that education did the individual so much good that he should be prepared to make certain sacrifices like postponing marriage or the purchase of an automobile in order to obtain it. Even in those times, however, some graduate students did marry and then it was the spouse who made the sacrifice. Many a student has thus been said to have worked his way through school "by the sweat of his *Frau.*"

Nowadays marriage has become the accepted state for most graduate students. Universities often provide housing for families, or at least parking space for their trailers, and fellowship programs provide extra allowances for dependents. Many graduate students are married to other graduate students and both receive financial aid in the form of fellowships or salaries for teaching duties. The sweat still appears on the brow of the *Frau* but more

as the result of healthy exercise than of forced labor. The traditional model for the graduate student was an ascetic, self-denying celibate monk devoting all his energies to the pursuit of knowledge. Now his life is a curious combination of bourgeois security and Bohemian unconventionality. The bourgeoisie features include his stable fellowship income and his married state. The Left Bank Bohemian atmosphere stems from his preoccupation with intellectual and artistic matters, the temporary and often makeshift nature of his housing arrangements, and the casual quality of his social life.

The reasons for this striking change in status and outlook are too complicated to discuss in detail here. Our major concern must be with the financial arrangements that made it possible. There is nothing particularly novel, of course, about the idea of providing scholarship help to poor but promising students. The new thing is the scale on which it is done. Both the number aided and the amount each individual receives have gone up enormously since the war. The change has been most striking in the natural sciences for several reasons. The role that scientifically trained people played in winning the last war and planning for the next is widely recognized both by the public and their representatives in Congress. Generous appropriations have enabled the National Institutes of Health and the National Science Foundation and certain other government services to establish extensive pre- and post-doctoral training programs. Additional grants directly to universities have improved facilities and enlarged the staffs available for graduate training. Some of these funds can be used to support the students themselves. The generous research grants enjoyed by all competent science departments are also used to support graduate students who fail to receive pre-doctoral fellowships. More often than not the work

done while serving as a paid research assistant provides a useful training experience. Frequently it contributes to meeting the thesis requirement. All these government subventions are in addition to the traditional support from private individuals and corporations. Corporate giving to universities is in fact increasing rapidly as more and more businesses recognize the economic importance of scientific research.

The result of all this is that just about anyone who needs it can get financial help for graduate studies in the natural sciences. The level of support varies somewhat with the ability of the student and with certain other circumstances, but no one intellectually and morally capable of graduate work, in science at least, should abandon the prospect because of fears about meeting his need for bed, board, and tuition. His standard of living may not immediately be quite that of some of his college classmates, but he will very probably do as well or better than most of them in the longer run. In any case, he will enjoy approximately equal conditions with those of the other graduates with whom he is living. Everyone will have much the same sort of apartment and the same sort of doubtfully reliable secondhand car. Social occasions will be informal and inexpensive. No one will expect steak and champagne except perhaps to celebrate the passing of general examinations or the completion of a thesis. Furniture is likely to be handed down from earlier generations of graduate students who will have found it too expensive and cumbersome to take with them when they drove off to take their first job. The point is that the life of the graduate student lies pretty much outside the status struggle which is said to be characteristic of many other kinds of life in America. If graduate students are judged at all by their colleagues,

it is much more likely to be on the basis of what they are than on what they have.

At this point a voice from a former generation cannot forbear to comment on one matter which can throw our generally favorable picture of the financial affairs of the graduate student badly out of line. To the astonishment of sociologists, population experts, and what used to be referred to as prudent men, the current younger generation has suddenly reversed the long-term trend toward smaller families. This is not the place to discuss all the complicated issues that go into the making of such choices. Nevertheless, I can't help pointing out that children do make demands on parents and in one way or another hamper their freedom of action. Sir Francis Bacon put the matter in his usual penetrating and forthright way when he said, "He that hath wife and children hath given hostages to fortune." Much as one may sympathize with the American girl's wish to demonstrate her biological soundness as early as possible, it should seem that one such demonstration should suffice during the family's graduate school stage. A baby every year reminds one of a quotation from another great Elizabethan, "The lady doth protest too much, methinks."

It should be obvious that more than one or at the most two children greatly increase the family budget. A larger apartment, mounting medical expenses, increased outlays for food and clothing, all make financial demands which are hard to meet even with the dependency allowances included in some fellowships. If for any reason the mother is unable to carry a full load of work even temporarily, the cost of additional help can throw a young family into debt in almost no time at all.

The financial problem is not the only or even the most

important thing to be considered. The early years of becoming a scientist demand continuous concentration of one's physical and intellectual energies. Only the exceptional man or woman can achieve the level necessary and at the same time give adequate attention to the demands of a number of children, which may range all the way from diaper-changing to conferences with teachers about problems of social adjustment in school. In former times most men simply did not assume the responsibility of fatherhood until after they were firmly established in a trade or profession. Aside from the purely financial aspects of the matter, it seemed much wiser to train oneself for these two very different occupations one at a time. It still seems wise to me.

Notes

[1] For total elapsed time between the A.B. and Ph.D. degrees, cf. *Graduate Education in the United States* by Bernard Berelson, New York, McGraw-Hill Book Company, Inc., p. 157, 1960.

10

Rewards and Satisfactions

The greatest satisfaction in being a scientist lies simply in being a scientist. My own teacher, Professor Walter B. Cannon of Harvard, used to say that he was unusually fortunate among men because he had spent his life doing exactly what he liked to do best and was paid for it into the bargain. Many other scientists have felt the same way.

Of course, the life of a scientist has its ups and downs. Almost every investigator will suffer from shorter or longer periods of frustration and disappointment. The outcome of any given piece of research is by its very nature uncertain. If one knew the answer beforehand, there would be no point in looking for it. As a matter of fact, the great majority of scientific guesses turn out to be wrong. The great majority of scientists therefore spend much of their time proving that they are on the wrong track. On other occasions the track may be the right one, but the available tracking techniques prove themselves to be inadequate and much time must be taken to devise new ones.

In general, the foregoing frustrations are amply compensated for in two ways. The greatest reward comes, of course, when everything turns out right and one gets a clear insight into a bit of nature or, rarely and gloriously, into a whole natural system. Such moments of truth may

not come very often, but when they do they make up for years of continuous hard work and intermittent frustration.

In the meantime, the typical scientist has been sustained by a second sort of satisfaction. This is a much more everyday sort of thing and has much in common with the pleasure that any skilled craftsman gets from exercising his craft. As we have seen, science depends on accurate observation of every aspect of the natural world. The techniques necessary for making these observations in sufficient detail and with the required degree of precision are often complicated and difficult.

It is customary for the layman to emphasize the element of manual dexterity which goes into the mastery of a craft or technique. Much is made, for example, of the "wonderful hands" of the skilled surgeon. The practitioners themselves are likely to be more aware of the intellectual and especially of the emotional demands laid upon them. As one develops a skill one must acquire a precise mental picture of the manual operations required and the order in which they can best be performed. By the use of the intellect one can devise ways of protecting oneself against neuromuscular slips. The good surgeon, for example, makes his original incision in such a place and of such a size as to avoid the necessity of exercising unusual dexterity at the bottom of a deep and narrow hole later on. Similarly, the cabinetmaker will devise a jig to guide his saw at exactly the right angle rather than trying to cut it freehand. All this mental and manual effort will not be successful, however, if one fails to develop the proper character. Above all, the skilled craftsman must keep his emotions under control. In the midst of some delicate procedure he simply cannot allow himself to become impatient or angry either at himself (the usual temptation) or at those around him. Any normal human being who has gone through the

long process of mastering the combination of manual, mental, and emotional abilities that form a craft or technique enjoys exercising it and takes a proper pride in the result.

In addition to these two rewards which stem directly from his work, the scientist derives a variety of other secondary satisfactions. Primary among these, perhaps, as pointed out in our chapter on the graduate student, is the pleasure of working and competing with one's intellectual equals. Although there are plenty of instances of bitter personal rivalries in science, the average scientist today gets on reasonably well with his colleagues both in his own laboratory and elsewhere. A considerable portion of his time will be spent in discussing his results with others in laboratory seminars, in regional and national meetings, and at occasional international congresses. Sometimes the arguments may get pretty heated, but for the most part emotional conflicts are kept within the bounds of the "friendly rivalries" found among intercollegiate athletes.

The disagreements in science are confined to the growing edge of knowledge. The great bulk of fact and interpretation is very generally agreed upon at any given time. As we have pointed out before, science is essentially a method for achieving agreement about the nature of things. If disagreement exists, the scientists on both sides devote their energies to making observations or devising experiments to convince their opponents and the scientific public in general. It is thus rather rare for scientific controversy on a given point to extend for more than five to ten years. Indeed, if convincing experiments cannot be devised to resolve a particular question in a reasonable period of time, the question is usually set aside as not a real question at all.

The scientific community has thus been able to avoid

much of the division and hostility that have characterized other aspects of human behavior. Such questions as whether God exists in three parts or only in one, whether kings rule by Divine Right or by the will of the people, whether Praxiteles was a better sculptor than Jacob Epstein, or Marx a better philosopher than Aristotle, are simply set aside as unanswerable with available methods. This procedure not only saves a great deal of time and effort, it ensures that the personal relationships between scientists are on the whole more cordial than those between economists, politicians, philosophers, and religious leaders.

The basic understanding among scientists means that the individual scientist is likely to have friends all over the world. Often these friendships arise through correspondence about a given problem on which work is going forward in several different countries. This correspondence, in turn, leads to face-to-face contacts at international meetings or to an invitation to work in a foreign laboratory. The importance of such interchanges for the progress of science is now widely recognized, and funds are generally available for traveling fellowships. Indeed, the good scientist is likely to be as well traveled a person as anyone except a modern Secretary of State. Unlike Secretaries of State, however, the scientist is almost always assured of the warmest sort of reception and the most open sort of interchange of ideas when he reaches his destination. Indeed the universality of science is perhaps no more convincingly illustrated than by the warm welcome received by Western scientists traveling behind the Iron Curtain. In spite of the fact that Communist political leaders have tried to enforce certain doctrinaire attitudes on the practice of science, the great majority of Soviet scientists have resisted the attack and speak a language easily understood by their Western colleagues. It is both a deep personal satisfaction

and a basis for hope in a more friendly world to visit the Soviet Union and find one's friends thoroughly familiar with what one has published on a given subject. Not only do they know what we have done, they are very likely hard at work confirming or disproving with exactly the same outlook as the scientific community elsewhere.

Time was when the spiritual satisfactions of being a scientist had to be bought at considerable sacrifice of material well-being. I can remember during my student days when an older colleague advised us that it was probably unwise to embark on a scientific career unless one enjoyed an independent income. This is no longer the case. As a group, scientists probably do about as well financially as any other group. Very few scientists, of course, reach the really high brackets occupied by the top business executives, movie actresses, lawyers, and surgeons. But the average scientist does a lot better than the average actor and is probably not much worse off than the average businessman, lawyer, or physician, if lifetime income and various fringe benefits are taken into account. Furthermore, if his money income is lower, he is likely to be living in a community which does not set a high value on material consumption. He is thus freed of the necessity felt by many business and professional people to keep up a certain appearance of affluence.

The three chief sources of employment for scientists are the universities and colleges, industry, and government. In 1960 there were slightly over 200,000 persons who registered themselves as scientists in the United States. Almost half of them were employed in industry or were self-employed. Twenty-eight percent were in educational institutions and 16 percent in government institutions, exclusive of the military services, but this statistical picture must be interpreted with some caution. As we have seen,

it is not always easy to differentiate between scientists and engineers, and there are other difficulties of classification that tend to confuse the picture. It is probable that the universities have a higher proportion of pure scientists and that university people are freer to choose their own problems and working conditions than are the employees of the other two types of institutions.

University and college scientists are of course expected to spend a certain proportion of their time in teaching. In the smaller and less well supported colleges, teaching may occupy most of the faculty members' time, with research squeezed into evenings, weekends, and vacations. The most productive scientists at the university level may be excused from all undergraduate teaching, but almost all give some time to graduate students both in seminar courses and in the informal apprentice-master relationship characteristic of academic research laboratories. Many scientists regard the opportunity for teaching as the most valued part of an academic position. Others make rather a point of complaining about it as an intolerable burden which only interferes with the progress of research. These differences in opinion largely reflect differences in the temperament and value systems of individual scientists, but there is an element of fashion in the situation as well. Many excellent scientists are known almost as much for the quality of their students as for their own individual contributions to knowledge. Most teachers with normal feelings for other human beings experience a deep sense of satisfaction in watching their students develop and go forth to establish their own laboratories and produce work of distinction. Even more immediately, many teachers find that their own research profits from the participation of graduate students. At the very least, the graduate student brings with him a bouncing energy and enthusiasm for tasks which may

have become routine and a bit tiresome to the senior staff. More important are the fresh, intellectual approach and the ability to ask new questions about old procedures. These serve to keep the teacher young by forcing him to examine assumptions that he may have taken too much for granted in the past. Further information about the satisfaction and rewards of the scientist who is also a teacher will be found in the delightful account given by Professor Fred Benjamin Millett in a companion volume of this series.

Scientists who do not develop a paternal feeling for students, or who regard their own work as so important as to require all their energies, may prefer positions in industrial or government laboratories. They are likely to feel, however, that here too their time is not exclusively their own. Industry is increasingly recognizing the value of so-called pure or basic research, but the fact of the matter is that the overwhelming majority of scientists in industrial laboratories must give a substantial part of their time to solving problems referred to the laboratory by nonscientists or in frankly routine matters such as quality control and testing of new products.

Nevertheless, industry does offer certain advantages not ordinarily found in academic laboratories. Certain types of heavy equipment may be more available, and there is often a supply of creative engineering talent to help in the design and construction of new apparatus. Industry is also equipped to provide large numbers of new chemical compounds which can be rapidly screened for their usefulness in the solution of certain research problems. Finally, if one likes to see tangible, practical results emerge from one's scientific speculations, he will probably find his wishes more promptly realized in an industrial than in a university setting.

As far as material rewards are concerned they are slightly better in industry than in education. But here again some qualification is necessary. At the moment there is, and probably for some time to come there will be, an overall shortage of scientists to fill the nation's rapidly growing needs. Competition for the really original and most productive type of worker is particularly keen, and there is a considerable variation from field to field. A paleontologist or taxonomic botanist is less sought after than a solid state physicist or molecular biologist, for example. Competition is changing the market rapidly, and it is probable that the salaries available four or five years hence will be considerably higher in several categories than they are now. With these qualifications in mind, it may be said that the average newly hatched Ph.D. may expect a salary of from $6,000 to $9,000 a year. The lower figures are characteristic of colleges and universities, the higher ones of industry, with government laboratories somewhere in between. At more senior levels, the very highest salaries are still paid by industry, but the number is probably a good deal less than is often thought. The great bulk of scientists with more than ten years of experience will be found in the $10,000 to $15,000 bracket whether in industry, government, or educational institutions. Although the beginning and perhaps the average salaries of government workers compare favorably with those in the academic world, government at present has a relatively low ceiling. Currently, the top for working scientists (that is, excluding a handful of scientific executives) is in the vicinity of $19,000 per year. It is not uncommon for the better universities to pay their top scientists as much as $25,000, and a few receive as much as $30,000. Universities have a salary scale for the various academic ranks, and the salaries

of the scientists are in some sense tied to those of the teachers in other deparments. In practice, however, the scientists tend to be promoted earlier than people in the other departments, and they are more often found at the top of the various brackets. In other words, they tend to become assistant, associate, and full professors earlier than the majority of their colleagues; and if the scale for full professors varies between $15,000 and $25,000 per year, it is likely that the science professors constitute the majority in the $20,000 to $25,000 range. This situation is clearly the result of supply and demand and does not reflect an opinion of academic administrators that scientists are better in any absolute sense. In fact, many academic people look down their noses a bit at scientists as not being interested in the finer aspects of life.

At the higher levels, competition among universities for outstanding scientists puts increasing emphasis on matters other than salary. The really good scientist is not primarily interested in money or in an unusually luxurious standard of living. His hopes for a large salary are often based on his interest in providing his children with the best possible education. After he has reached the $25,000 bracket, these hopes are largely taken care of; and in any event, increases beyond this level encounter heavy taxation.

In view of these facts, competition for the best men increasingly takes the form of offers of better laboratory facilities, more numerous and higher quality colleagues, and so on. It is not unusual to offer to construct a whole new laboratory and provide three or four new faculty positions in order to attract an outstanding candidate. Industrial and government laboratories frequently use inducements of this sort also. Indeed, with the low salary ceilings imposed by legislation, government departments

frequently have to rely on the lushness of their laboratories and freedom from routine teaching duties in order to attract the best investigators.

No discussion of compensation these days is complete without some remarks on fringe benefits. In this respect most scientists are now clearly better off than lawyers, doctors, or businessmen. In the first place, the academic, and to a large extent the government, scientist has stability of tenure. Once he reaches a certain stage, his job is virtually guaranteed until the end of his active life. Opinions differ as to whether or not the tradition of permanent tenure is a good thing, and I do not propose to argue the matter here. It is simply a fact that university professors and, to a somewhat lesser extent, civil servants have it and that it is one of the most jealously guarded of academic perquisites.

All three categories of scientists also enjoy pension, life insurance, and, to a rapidly increasing degree, medical insurance plans. These cannot be described in detail here since they differ considerably from place to place and are usually so complicated that few people other than a handful of attorneys and controllers really understand all their provisions. However, there are a couple of points of a general nature which may be worth bearing in mind, although I share the opinion of many old-fashioned people that the current younger generation is far too preoccupied with matters of financial security. Generally speaking, industrial and government pension and insurance plans terminate when the employee takes another job. Academic pension plans, on the other hand, are ordinarily transferable, that is, the balance built up during employment in one institution remains to the credit of the employee when he leaves. This has two salutary effects. Insofar as the individual is concerned, he is less tied down to one job and is free to

go where the opportunity for productive work may be greatest. This, in turn, makes it possible for the academic community to exchange personnel in a flexible and progressive way. Industrial and especially government laboratories often develop rather static and rigid structures, in part because of the nature of their pension and tenure arrangements.

To complete the financial picture, many scientists add to their regular salaries by collecting royalties on monographs and textbooks. Many who hold academic appointments also collect special consulting fees from industry or government, but ordinarily industrial and government scientists are not allowed to supplement their income in this way. It is in fact somewhat of an anomaly that the university scientist who is theoretically the most completely dedicated to the pure pursuit of knowledge is most often found selling his services for extra pay. Often this extra work is taken on at considerable sacrifice not of the scientist's own leisure time but of time which he ought to be giving to his university duties. A few institutions have tried to stem the tide of this advancing wave of commercialization by adopting a "full-time" principle, but few have been successful. No one seriously objects to the collection of royalties for books which grow out of a scientist's professional work. Such fees have long been regarded as part of the scholar's regular income. In point of fact, they represent a sort of extra bonus for doing what one is supposed to be doing anyway. In most cases, royalty income is modest in size, but a really successful textbook can bring its author a fortune of several hundred thousand dollars.

Consultation fees from industry raise several rather difficult questions, and at present they constitute a substantial part of the incomes of many faculty members, especially in engineering schools. Some people may spend as much as

half their time in consulting work for which they receive compensation amounting to several times their academic salaries. Obviously such a person is likely to suffer from divided loyalties, and in some cases students and colleagues may legitimately wonder whether he is primarily interested in science at all. The situation is further complicated by the fact that opportunities for such work are far from evenly divided among the various scientific fields. Much of physics and chemistry has direct application to industry. Certain areas of biology related to the drug industry or to commercial agriculture are also lucrative sources of consulting fees. On the other hand, archeology, paleontology, and certain of the most basic areas of the classical fields of science are less financially fertile. Furthermore, most of the important areas in the humanities give little opportunity for financial exploitation. This unevenness of the consulting business tends to set up strains and jealousies within university faculties, and one may well ask why university administrations continue to condone and in some cases even to encourage the practice. The answer lies again in the current shortage of scientists and the difficulty almost all institutions have in recruiting and holding a competent faculty.

No discussion of fringe benefits would be complete without mention of the scientist's numerous opportunities for travel. Odd as it may seem, there is probably no group in the country that is more familiar with the great resort areas of the world. In part, the high mobility of the scientist grows out of the consulting function just mentioned. Both government and industry make use of scientists in the conduct of their own business. Large numbers of scientists go to Washington and to military installations both here and abroad to give their help both in the formulation of overall military policy and in the development of particular weapons. In addition, equally large numbers meet at regular

intervals to give advice on the distribution of government money for the support of research both in the government's own laboratories and in civilian establishments as well. So extensive has this activity become that at least one commentator has wryly observed that the government has decided that the national welfare and security now require that an air cover of scientists be maintained over the country at all times. This remark neatly summarizes the rueful regret at leaving their laboratories combined with pride at being recognized as indispensable which characterizes the attitude of many scientists towards their federal obligations.

An even more common and usually more rewarding motivation for scientific travel lies in the need we have noted before for frequent communication of scientific results. Literally hundreds of scientific meetings are held for such purposes each year. These range from groups of twenty to thirty people dedicated to a single topic, such as the structure of a single protein molecule, to huge international congresses dealing with a broad field like biochemistry. The large meetings must of necessity be held in large cities or resort towns with ample hotel accommodations. European capitals are a favorite site for the international congresses, but occasional visits are made to North and South America and increasingly to the Far East, especially Japan. The smaller conferences frequently select resort hotels either in the mountains or by the sea, often in the off season in order to take advantage of the lower rates. I know of at least one such group, however, which has met for over twenty years in the Laurentian hills during the height of the skiing season.

The tone of these meetings is a good deal more serious than that encountered in the national conventions of many businesses or of social and fraternal organizations which are such a common feature of American life. Most of the

time is, in fact, spent in discussion of scientific matters. Nevertheless, some time is usually allowed for seeing the local sights or for participating in the recreational activities commonly found in resort areas. The sight-seeing is often arranged by knowledgeable members of the local community so that the visiting scientists can see more under more intelligent and sympathetic guidance than would be available to the conventional tourist. Often he will be entertained in the homes of local scientists or other persons with broad cultural interests and larger homes than those ordinarily available to professional people.

Like everything else in this world, the amenities of travel are not evenly distributed throughout the scientific community. Obviously the more capable and the more enterprising are more likely to be invited to such scientific meetings and to find means of getting most of their expenses paid. Personal taste of course plays a role. Some very capable scientists eschew all meetings as a waste of time, and others may tend to overdo it to the point of becoming little better than scientific bums—to borrow an analogy from the tennis world.

Taking it all in all, however, the average productive scientist in one of the currently fashionable fields has, by the time he has reached forty-five years of age, been to Washington more times than he cares to remember, to most of the other large cities of the United States, to all the major capitals of Europe at least once, and has probably made one or more trips to Latin America or Asia. He has also spent a week or so each in a number of such internationally known resort areas as the Rocky Mountains, the Riviera, the West Indies, and the Alps.

If he is really outstanding, some of his travel has been for the purpose of receiving special awards which in the United States take the form of honorary degrees, gold medals, and

visiting lectureships. Foreign countries have all these and special government orders of merit as well. The ceremonials attached to these awards vary in duration and complexity, but some of them, especially in foreign countries, may extend for days and provide the recipient with a personal experience of the pomp and adulation which used to surround the lives of hereditary nobility and military heroes. The top event of this character is, of course, the awarding of Nobel Prizes in Stockholm each December. This coincides with a traditional Swedish festival, one part of which involves beautiful girls with candlelit crowns who bring breakfast in bed to distinguished citizens, a group which includes the season's crop of Nobel Laureates.

Although it is difficult to get inside of people sufficiently to know their motivations, it seems unlikely that any very large proportion of scientists chose their careers or did their work primarily in pursuit of a gold medal or a Nobel Prize. Certainly, these tokens are nice to have, but the basic rewards and satisfactions of the scientist are still found, I think, in the pleasure of satisfying one's own curiosity, the delight in mastering the necessary observational skills, and the satisfaction of working as part of a community of scholars.

11

Day of a Scientist

So far in this book we have been standing a little back from science and scientists and describing what we can see. Insofar as has been possible, I have tried to give what will be defined later as an *objective* account. What a person who is considering science as a career really wants to know, however, is how it *feels* to be a scientist. As I shall try to show later on, the sharing of other people's *subjective* feelings requires techniques quite different from those of science. In this chapter, therefore, I shall try to get closer to how a scientist feels by describing a day in the life of a hypothetical scientist.

Our hypothetical scientist is Bill Stone. He woke up at six o'clock the other morning and began to wonder what he could do to purify the X protein. There was a lot of interest in this unusual substance just then because Goodwin and his colleagues out on the West Coast had recently reported some experiments that made it look as though either it or some closely related polypeptide was important in initiating limb bud formation in tadpoles. Bill had been working on the chemistry of sulfur-containing proteins for some time and had, in fact, written a pretty good thesis on the cross-linkages in insulin. The X protein had turned up while he was collaborating with one of the younger men in the department of surgery on the problem of wound healing.

Everyone had recognized since the time of Ambroise Paré that wounds heal much faster in young people than they do in the elderly, but until recently most people who thought about the problem at all simply put it down to such general factors as better blood circulation and the greater vigor of young organisms. Bill and his surgical colleague thought there might be something more specific than that and had embarked a couple of years before on a long program of extraction of tissue in the process of healing. During the first year he had managed to get two or three preparations which served to have some effect in speeding the healing of small cuts on the corneas of rabbits.

The suggestion for using the cornea as a test object had come from a friend in the anatomy department who had been using the anterior chamber of the eye as a place to grow ovarian tissue. Apparently, this technique had been developed years ago by the early workers on the estrous cycle, but Bill as a biochemist had never heard of it. The cornea had turned out to have a lot of advantages as a place to study wound healing. It was very easy to observe, especially if one employed the old fluorescein trick which made the unhealed part glow in ultraviolet light. Furthermore, there was no blood circulation to complicate the problem. At first there had been a good deal of irregularity in the speed of healing in different rabbits, but this had been straightened out by using an inbred strain and buying the lettuce on which they were fed from a local truck gardener who had a greenhouse where he raised lettuce all year around as a sort of hobby. Ordinarily, commercial lettuce from Texas seemed to lack something essential for wound healing in the rabbit during the winter months. It might, of course, be Vitamin C, but it seemed inconceivable that a herbivore like the rabbit could be Vitamin C deficient under ordinary conditions. Bill had made a mental note to

get one of his better graduate students to look into the problem: might make a good thesis problem if things broke right.

But he mustn't let his mind wander around like this, even if it was still early in the morning. He had to be in the lab by eight-thirty to get his technician going before his lecture to the first-year class in organic chemistry at nine. By eight-thirty too, he should have some reasonable suggestion for getting rid of that trace of lipoid which kept gumming up the efforts to crystallize Protein X. The usual organic solvents took the lipoid out all right, but they seemed to change the protein in some way. Sometimes the activity of the preparation seemed unimpaired, but other times it lost at least 50 percent of its potency and the electrophoretic pattern became less clear-cut.

Jane seemed to be still asleep. She had come home late from a school board meeting at which there had been a hassle about whether a Jewish girl should be allowed to take the part of the Virgin Mary in the Christmas play, and they had stayed up some time discussing the problem over a drink. Bill wasn't very interested in community affairs himself. He found that he got terribly impatient at parent-teachers' meetings and said things that made people mad. As a conscientious person and one who was particularly aware of the need for upgrading the schools if the country wasn't going to go into a gradual decline, he regretted his lack of skill and patience in these matters. But he tried to salve his conscience with the thought that his own scientific work probably had a social value and that his teaching of advanced students contributed to the education of at least some Americans. Finally, he regarded as his greatest personal sacrifice to the community the fact that he let his wife join the school board when that citizens' group put the heat on her last fall.

Last night's conversation was typical of the kind of moral and intellectual support he tried to give her every so often, but she had not found it very helpful when he had suggested that she point out to the rest of the board that the original Mary had been Jewish too. Jane had given a wry smile, but she had known right off that this was just the kind of argument that seldom swayed a public meeting, despite its logic. And anyhow it had no bearing on the petition the board was expecting to receive in a day or two from an orthodox group who wanted to abolish Christmas, or at least the Christmas play, entirely.

All things considered, Bill decided he would let Jane sleep and get his own breakfast. He pushed the button at the side of his bed which his twelve-year-old son, who was showing signs of becoming an engineer, had rigged up to start the coffee percolator downstairs and hurried into the bathroom to shave. He was probably the last person in town to use a straight razor, but he kept it up because he was proud of his skill in wielding the old-fashioned blade, just as he was proud of his ability to make the old air-driven ultracentrifuge in his lab give as good pictures as the new Spinco that the graduate students insisted on using.

Incidentally, he thought, as he began to strop the blade, he must remember to do something about improving the scheduling of the Spinco. Everyone in the lab seemed to be working on some problem or other that required this particular instrument. At first he had given responsibility to Assistant Professor May for seeing that it was kept in order and made available to all on an equitable basis. May knew the instrument inside and out; in fact, it was alleged that he had built quite a good centrifuge as a science project when he was in prep school in the East, where he had gone on the local alumni scholarship. Nevertheless, he had been a flop at scheduling the centrifuge. For one thing, he was

too respectful of his elders whom he had learned to call "Sir" at prep school. He had now almost abandoned the practice, but he would fall into it if someone with a Boston accent or, above all, some Britisher came to the lab to give a seminar. But he still wasn't able to stand up to Associate Professor Ash who had been working for years on the structure of avian hemoglobin in an attempt to explain the elliptical shape of bird red cells. Ash had hit some sort of jackpot when he was an instructor and had been rapidly promoted to a tenure position before it became clear that his early papers were largely attributable to the momentum he acquired during a traveling fellowship spent with Sir Frederick Hopkins in Cambridge. He did have an extensive knowledge of the early biochemical literature and was a great help to the graduate students in guiding them through the more pedestrian parts of their theses. Furthermore, he pulled his weight in the department by giving year after year the course in quantitative analysis which none of the younger men wanted to do. In spite of all these assets, he had never caught on to modern work, and there was really no excuse for allowing him ten daylight hours a week on the ultracentrifuge for his crumby hemoglobin problem. The worst of it was, two of Bill's best students had to work from midnight to four in the morning twice a week in order to finish up their paper in time for the April meetings.

As he walked back to the bedroom to dress, Bill thought, as he had many times before, that one way of solving the problem was to buy another centrifuge. With all the accessories, the gadget cost about \$30,000—much too much to be taken out of the regular departmental budget. Besides that, the Dean and the Provost, both of whom were humanities types, had scarcely gotten over the shock of paying for the first one. Bill had, in fact, put in an application to the National Institutes of Health, but the Study Section

which passed on such matters for the Surgeon General had recently been rather sticky about insisting on a clear description of exactly the problems for which the apparatus would be used. Along with a lot of other people, Bill thought this was ridiculous in the case of a general-purpose apparatus like a Spinco analytic and had said so. Fortunately, he had a couple of good friends on the Study Section who felt the same way. One of them had three Spincos in his own lab—all bought with government money—and he certainly couldn't have described specific problems for even one of the three, much less have seen to it that they were used only for these purposes after they were obtained. But the Study Section wouldn't meet for another couple of months, and there would be additional delays while Congress debated how much the NIH should get next year and while the application traveled on up from Study Section through the Council to the Surgeon General's office. Even with the best of luck it would take at least a year before a new centrifuge could be installed and working. In the meantime, he would have to replace May with somebody who would throw his weight around a bit more.

In any case, May had had the headache long enough and deserved to have some more free time to do his own research. Having decided this, Bill turned his attention back to his own problem. Apparently, he had been thinking about it subconsciously as he mulled over his administrative difficulties, for it occurred to him as he was tying his tie that he had better abandon any further attempt to extract the lipoid from the protein with organic solvents and try adsorbing out the protein on a special cellulose column he had just read about in *Nature*. He could start his technician reading up on the technique and get his secretary to order the necessary stuff as soon as he got to the lab.

By the time he got to the kitchen, the coffee was well

perked, and he was a bit surprised to find his teen-age daughter Carol frying some eggs and bacon for them both. Carol was something of a puzzle to him. She had always been on the honor roll in school with especially good marks in English and French; she played the cello in the orchestra and seemed to have a variety of intellectual and artistic interests. But she "hated" science and despised math even though her marks in these subjects never fell below a B. Recently all her marks had fallen off a little, and she was in danger of falling to the second group of honor students. She had begun to go to dances almost every week, and it seemed probable that the time she spent on the telephone could easily explain the falling off in her schoolwork.

Indeed, she explained her early appearance in the kitchen as owing to the necessity of finishing a French paper before she left for school at eight-fifteen. Watching her competent handling of the frying pan and her efforts to make the breakfast nook something more than a mere workbench, it suddenly dawned on Bill that she might be trying herself out as a homemaker. And then came the thought that someday, and maybe quite soon, he would have to release this sweet, beautiful, really unusually talented girl to some oaf in chinos who wanted to live in a trailer and work his way through graduate school. Even worse, he might not be a graduate student at all but some dull salesman type who wanted nothing better than to belong to a suburban country club.

Like most biochemists, indeed like most natural scientists, Bill had been so much taken up by biochemistry that he really had not had much time or incentive to ruminate about other aspects of life which showed relatively little promise of ever being put into some neat formula. His own sound natural instincts had taken him into marriage and through the early years in which the children were growing

up. Jane was a good girl with an excellent college degree in history and government and knew a lot of things about life that Bill didn't. He was quite happy to leave the complex human relations problems of family life to her. Indeed, during the early years of their marriage, Bill really wasn't home an awful lot. He was working on a problem which required observations every three hours for eighteen hours of the twenty-four, and since it took him over an hour to get from their house to the lab, the result was that at least three evenings a week he didn't get back until one or two in the morning. Jane seemed to take all this without too much stress, although she clearly didn't like it very well when she had to go to the hospital alone when her first baby was born because Bill was working in his lab and the central switchboard was closed. It was at about this time that Bill overheard an intellectual at a cocktail party quoting some Frenchman to the effect that all the troubles of the world boil down to the fact that women love their men and men love their work. Years later he had still remembered the remark. Recently, however, he had given more time and energy to domestic matters. The children were reaching an age at which they could clearly profit from the attention of two parents, and, in any case, he was finding them more interesting and attractive. Even more important was the fact that as he rose in the departmental hierarchy and served on more and more panels and committees, he was beginning to encounter those human relations problems which seemed so remote when he was a student. Jane had been very helpful in steering him through several such crises.

Carol slipped the eggs out of the frying pan, added a couple of pieces of bacon which had been drying off on a bit of paper towel, and sat down opposite her father.

"Daddy, do you think you could come with mother to

the French play next week? I'm playing the ingénue part and it's quite cute."

"You mean the part's cute or you're cute?" Bill was never quite sure about the force of this particular adjective as used by his children and their friends.

"Well, both I guess," replied Carol, and grinned instead of blushing as Bill's sister Madeline would have done.

"It sounds good," said Bill and slipped out of his pocket the little black date book which had become almost a part of his anatomy. "Can't do it Tuesday; I'm in Washington. Wednesday there's the supper club at which I have to introduce Professor Cinque from Paris with the latest word on Messenger RNA, and Thursday I have to speak to a group of businessmen on how a college chemistry department can help build local industry. This is part of the Dean's campaign to get more local support for the University. I hope your show is on Friday night which so far looks clear."

Carol, who had been looking more frustrated as this recital went on, brightened noticeably and said, "Oh good, we're giving it both Thursday and Friday, and the parents are supposed to come Friday because Thursday is kind of a dress rehearsal."

"It's a deal then," said Bill, and his parental duties over for the moment, he slipped off to the cubbyhole he had built himself in the attic as a sort of study. There he worked for an hour on the short paper he planned to give at the April biochemical meetings. He used to do such work in his office at the lab or in the library, but he now found it best to write at home where he could be relatively free from interruptions and in the early hours of the morning before his mind became distracted with other things.

About eight-ten he stepped into his Volkswagen and set out for the lab. By the time he arrived, his secretary, Mrs. MacAvoy, had already gotten the mail sorted and was ready

with a list of questions which served to get the day started. Mrs. MacAvoy was a real jewel. Actually, he had known her for over twenty years, and they were on a first-name basis. Her husband had been one of the most promising students in Bill's time but had volunteered promptly for the Navy and had been killed while testing some of the early radar models under conditions of active service. She had been taken in as a typist in the department and had worked herself up to a position of indispensability and considerable power. She greeted him with a smile which combined old friendship, considerable respect, and a self-confident assurance that everything would go well if he just paid attention to her questions.

"Good morning, Bill, you'll want to see this right off. The National Science Foundation has just written to say that the appropriation for Bob Smith's work has been granted in just the amount you asked for. Here's the acknowledgment for you to sign. The rest of the mail is routine and can wait. I'll draft some replies when I get a moment during the day. Here's what you dictated yesterday, and here's the second draft of your paper for the *Biochemica Acta* except for the graphs which the photo department hasn't returned yet. Incidentally, that new girl in the typing pool is a whiz, but I'm afraid she'll be leaving in three or four months to have a baby.

"Next, I'm afraid, is a headache. I can't make head or tail of that paper Stan Roberts just handed in for typing. He can't write worth a darn, and the tables don't fit with what he says in the text. I'm afraid you'll just have to have a look at it yourself."

"OK, I'll stick it in my briefcase and work on it over the weekend. Sometimes I wonder what those guys in the English department do to earn their pay. None of their graduates seem to know how to write an understandable

sentence, much less a paragraph. Maybe the trouble is that science requires people to be really clear about what they have in mind while other subjects don't."

Mrs. MacAvoy, who had been an English major herself and had the same feeling for grammar that a physicist has for mathematics, merely smiled at this and tried to say something about the application forms for the big training grant which the department planned to ask for from the National Institutes of Health.

By this time though, Bill had had enough administrative detail and passed by into his personal lab next to the office. There his technician, Betty Smith, was already busy arranging the glassware which had come back from the central dishwashing service and generally putting things to rights. She was delighted to hear that he had decided to abandon for the time being those tiresome and frustrating experiments with the organic solvents, many of which smelled bad and all of which were in danger of boiling over and catching fire unless you watched them like a hawk. Hence the emergency showers at each end of the lab under which a flaming technician was supposed to step calmly and pull the chain that would start the fire-quenching shower of water.

She was doubly glad to hear that she would have the opportunity of working up a new technique more or less on her own. She was a bright girl who had had to break off her graduate training when her mother became ill and ran up a lot of doctor's bills, but she hoped to return in a year or two. In fact, if she did well this year, Professor Stone had promised to help her get a fellowship which would pay her almost as much as she was getting as a technician.

Bill just had time to outline his plan and give her the reference to the *Nature* article when he had to rush off to

the nine o'clock lecture. In spite of the fact that many of his friends and associates made rather a point of regarding teaching as a task to be avoided or gotten over with as soon as possible, Professor Stone found that he really liked it. That psychiatrist who talked at the last meeting of his dinner club would probably say that deep down he was some sort of an exhibitionist. He was, as a matter of fact, a good lecturer, and he enjoyed feeling the class come alive when he had given a particularly dramatic demonstration or had succeeded in clarifying some obscure point in regard to the nature of the chemical bond. He couldn't help being gratified when several of his senior students came to say that they had never really understood van der Waals's forces until hearing his explanation from the lecture platform.

Furthermore, he knew that some of the greatest names in chemistry, people like Emil Fischer, Hoppe-Seyler, Frederick Hopkins, and in our own time Theorell, Linderstrom-Lang, and Krebs were known as much for the people they had trained as for their own personal research. Like a good many scientists who have come to doubt the idea of personal immortality but still find themselves uncomfortable at the thought that death is the end of everything, Professor Stone looked to one or two of his best papers and to several of his best students to carry his name and something of his personality down through the coming years.

All these thoughts went through Stone's mind as he walked to the lecture hall nodding somewhat abstractedly to some of the students whose faces he recognized as they passed. The matter of teaching had been more than usually on his mind the last couple of weeks since he had received a tentative letter from the organizer of a brand new Institute for Research on the Brain and Behavior down in Texas. Some very rich oilman had finally decided that there

was no point in any more Cadillacs and had given a huge tract of land in west Texas as a site for the new institute. As he had included a number of producing wells with the land, it looked as though the income would amount to something between five and ten million dollars a year. The name of the new director, a pharmacologist who had developed one of the better tranquilizers, had been announced, and he was now trying to assemble an outstanding staff representing all the various disciplines supposedly related to mental illness. Starting salaries were widely rumored to be $30,000 a year with free memberships at the local country and barbecue club and a credit card at Neiman-Marcus. There was some uncertainty about the last point but Jack Freedman, who was a classmate of the director and was something of a gossip, had told Bill at the last meeting in Atlantic City that the new institute would need something to balance the attraction felt by so many wives for the wonderful climate in La Jolla and Palo Alto.

At first Bill had been rather flattered to have been included in the really outstanding group of people said to be under consideration. The more he thought about it though, the more he had come to the conclusion he would turn down the offer if it came. In spite of the fact that the director had made quite a name for himself and had gotten any number of prizes for his tranquilizer, Bill didn't think much of his chemistry. Jane, who in a pinch would go anywhere he wanted to go, really didn't like Texas, and the credit card at Neiman-Marcus wouldn't compensate her for having to choose between two candidates for Congress both of whom favored the depletion allowance and neither of whom seemed very clear on civil rights. But the thing that really put him off was the emphasis put by the exploratory letter on the elimination of all teaching duties. It didn't seem right somehow to tempt a scholar to a new post by

trying to free him from one of the traditional obligations and privileges of scholarship. Furthermore, Bill had been to medical school and even though he had gone directly into chemistry without taking an internship and had forgotten almost everything he ever knew about a stethoscope, he was still sentimental about being a physician. As such, he took rather seriously the passage in the Hippocratic Oath about teaching the art to the sons of one's colleagues as if they were one's own sons.

Feeling this way, Bill had been glad to hear a few years ago that the Rockefeller Institute, which for fifty years had been devoted solely to research, had decided to obtain a university charter and accept graduate students. In the face of this it seemed a retrograde step to establish new institutes all over the country to take the best men away from universities.

The lecture today went well. It was the first of a series on aromatic or ring compounds, and Professor Stone always enjoyed telling of how Kekulé had arrived at his solution of the structural problem posed by such substances as benzene, phenol, and so on. Until his time, all the organic structures known were open, chainlike molecules with at least two or more ends. Kekulé had been discussing the problem with one of his friends on a visit to London, and as he went home on the top of the omnibus, he had a vision of atoms dancing about and holding hands. The dream recurred over many years, and finally, as he sat dozing one night in front of his fire, he began to see groups of atoms, as he put it, "gambolling before my eyes. This time the smaller groups kept modestly in the background. My mental eye, rendered more acute by repeated visions of the kind, could now distinguish larger structures, of manifold conformation: long rows, sometimes more closely fitted together; all twining and twisting in snake-like mo-

tion. But look! What was that? One of the snakes had seized hold of its own tail, and the form whirled mockingly before my eyes. As if by a flash of lightning I awoke; and this time also I spent the rest of the night in working out the consequences of the hypothesis." The hypothesis, of course, was the ring structure of benzene which lies at the base of all modern knowledge of "aromatic" organic compounds.

There is something *gemütlich* about this story, and Bill thought that it helped at least some of the class to feel that scientists are flesh-and-blood human beings who let their minds drift off when they should be doing their homework. The more sophisticated might also begin to grasp the role of metaphor in the creative process. His humanities friends at the faculty club always laughed when the physicists, who talked about such things more than the biologists and chemists, would say that the creativity of the scientist has much in common with that of the poet. But Bill, who wouldn't have said it himself, knew what they meant.

Bill hadn't had much time for literature in college, but a wise high school teacher had got him interested in Kipling just at the time when Kipling's talents as a poet were being obscured by hostility to his imperialistic tone. When his literary friends griped about science taking the warmth and color out of life, Bill felt some of the indignation of the old engineer M'Andrews when one of his lady passengers asked him, "Mister M'Andrews, don't you think steam spoils romance at sea?"

As soon as the lecture was over and Bill had answered the questions of the three or four students who came down to the lecture platform afterward, he went off to the laboratory of the professor of physiology, Nick Whittmore, for two hours of laboratory work. About six months before, he had been sitting next to Nick at a rather dreary dinner given

for the head of one of the great foundations which was considering a substantial grant to the University for the development of African Studies. Bill and Nick had been asked more or less out of courtesy since their interests were rather remote from those of the foundation man. Seated together some distance from the head table, they fell to exchanging regrets about the way their growing administrative duties had taken them "away from the bench." Both of them had made their reputations by using their hands as well as their heads, and they missed the sense of involvement with actual experimental work now that they were turning over so many of their ideas to technicians and graduate students to work out.

Nick had raised a more serious point when he said, "What worries me the most, Bill, is that, to be frank about it, the stuff coming out of our two labs doesn't have the same originality or what the Germans call '*Geist*' that it did when we were both assistant professors."

"I know what you mean, Nick. It's good solid stuff. Your recent review on the chemistry of the action potential was swell. You don't have to be embarrassed about comparing yourselves with any group in the country. But sometimes I wonder if a guy like Ferrari with his little lab off in the hills of Italy with almost no money, but time to think, isn't really better off when it comes to making one of the real leaps forward."

"And then there is B. R. M. Cooper in that dinky lab on the coast of England. I've visited his place, and I wonder how he gets anything done at all with that odd equipment of his, most of which he made himself. But did you notice his letter to the editor in *Nature* the other day on impedence changes in the head ganglion during learning in the octopus? That could be a real breakthrough—God how sick I am of hearing that word."

"The word's all right; it's the people who use it that get me down," said Bill. "Congressmen, university presidents, advertising men—did you see that ad the other day which was trying to claim that mounting the shift lever on the floor instead of the steering post was some sort of a breakthrough in automobile design? It makes me sick!"

"I suppose one of our biggest problems is the fact that we feel weighed down by the responsibility of seeing to it that our fancy and expensive labs pay off with some sort of creditable production each year. We must always worry that our graduate students have something to show for their conscientious efforts."

Bill thought so too and went on to say that he found himself picking problems which he was pretty sure could be solved in not more than a couple of years. This practice pretty well ruled out the taking of the big risks necessary to pursue the really important questions.

The upshot was that Bill and Nick had agreed to set aside three mornings a week to work together in a little isolated corner of the third story of the old physiology building. There was no telephone on that floor, and their secretaries were instructed not to send a messenger to them under any circumstances—well, perhaps if the old building caught fire.

They had selected a really tough, really important problem, and they told each other that they would work on it for at least five years before giving up. What they were after was some identifiable event in nerve cells which could be correlated with memory. The approach they were using was too technical to be discussed usefully here, but it involved a combination of the recording of the electrical events inside a single nerve cell, at which Nick was a real expert, with an effort to record a change in some of the

soluble nucleoproteins in which the nerve cells were known to be particularly rich.

Bill had been following very closely the work on changes in nucleoprotein synthesis which occur after virus infection. By tagging the relevant compounds with radioactive isotopes, it had been possible to show that in some cases infection of a cell was followed within minutes, possibly within seconds, by a cessation of normal synthesis and the initiation of virus formation. This phenomenon approached the time dimensions which people were beginning to describe for the setting up of permanent memory traces, and it looked as though the methods used by the virus boys could be adapted to the memory problem.

Some preliminary experiments with photographic emulsions had been promising, and today they were going to do an experiment with the microscopic bubble chamber they had devised with the help of the physics department. The physics boys had laughed and laughed when they first took the problem to them: "It would be hard to maintain the critical temperatures, pressures, and humidity on the appropriate scale. At the concentration of isotope you're using you'd get all gummed up with secondary radiations, and finally and above all, the bubbles in an ordinary chamber are much too large to give you the resolution you need. The whole point of a bubble chamber is to see things on a macroscopic scale rather than having to resort to microscopic analyses of photographs."

One guy with a beard finally had volunteered to help them, and one by one the problems had been pretty well licked—the bubble size difficulty by the simple expedient of adding a tiny bit of household detergent to the mix, nobody knew quite why.

Today they planned to look at eight slides with their

newly made microscopic bubble chamber, four from animals that were in the process of learning a conditioned reflex and four that had received the same stimulation but had failed to learn. All eight animals had received injections of equal amount of isotope labeled purine. The idea was to see if the learners showed an increased synthesis of nucleoprotein by fixing more of the radioactive isotope. The design had some bugs in it, and the experiment wouldn't be at all conclusive, even if it turned out as they hoped. Nevertheless a successful experiment would at least suggest that they were on the right track and justify putting in some additional refinements and controls which they had already thought of. The slides were marked in code by the girl who had made the thin sections of nerve cell they were going to look at. She was the only person in the lab who knew which slides came from the learners and which from the dull animals.

By the time they had finished the first four preparations, it was clear that one produced about half again as many tracks in a given time as had each of the other three. Nick's hand shook a little as he put the fifth slide on the stage and started the servos which controlled the humidity and pressure. The temperature was taken care of by the thermostat which controlled the small room they were in. After ten minutes he said, "Gee, Bill, it does look as if this one had 50 percent more too. And look here, do you see what I see? The extra ones all seem to be coming from the base of one dendrite about 30 degrees from the axon hillock." Bill, who had forgotten most of his neurohistology, took a look, and after Nick had pointed out the landmarks, he thought he could see the difference too. The rest of the morning was spent on surveying the other slides and rechecking the first one to see if it too showed a clustering of counts near one dendrite. It did, but when they had added everything up,

it turned out that four of the slides gave total counts of five to eight per minute, one varied from seven to nine, and three fell in the nine-to-twelve range. After looking at these figures for a while, Bill said with a rather half-hearted attempt at calmness, "I guess the next step is to find Barbara and ask her about that code."

Barbara was almost as excited as they were when they showed her the figures, and she fumbled a bit as she pulled the envelope containing the code out of the pocket of her lab coat. She didn't know much neurophysiology, but the general outline of the experiment had been explained to her, and she liked both men well enough to share their obvious excitement and pleasure. After a glance at the code Bill turned to Barbara with a quick "Those were damn good sections you made, little girl—let's go have lunch."

There would be time later to figure out why one of the preparations fell in between the others, and of course more experiments would be necessary to establish statistical significance, but it looked as if their Rube Goldberg bubble gadget was going to work.

Together they went into the adjoining conference room where most of the department had already gathered. Some of the people were half through their sandwiches, and the coffee had just about finished perking over in a corner. Associate Professor Work looked up as they came in and irreverently inquired, "Well, how are the two hermits today? Everything go well up in the clouds?"

Nick merely grinned and turned off further inquiries with "Yeh, the dew point did pretty good today," and asked if someone had a spare sandwich for Bill. A couple of the girls at the end of the table who were trying to reduce filled the request for the newcomers.

An intense-looking assistant professor took up the thread, "As I was saying when we were interrupted by the arrival

of the brass, I don't believe that fathead Frasier out there in Pasadena when he says he's measured an inside-outside potential in glia cells of 75 millivolts. As a matter of fact, I doubt if he got those clumsy electrodes of his inside a glia cell at all. I've tried it a hundred times, and when the anatomical sections come back, it always turns out that I was probably in some sort of a neuron."

"Maybe so," needled one of the senior graduate students, "but I just saw in the *Proc Soc* (*Proceedings of the Society of Experimental Biology and Medicine*) where he put his electrodes into a scar where there were nothing but glia and got the same thing."

Nick turned to a blonde, rather shy girl at his left and said, "Margot, why don't you tell the boys what you saw down in New Orleans, besides, of course, the inside of Antoine's and those *boîtes* on lower Basin Street."

"Well," Margot said, "Nick sent me down to see what Mike Finster in the zoology department is doing with that fish he's just found that can make his skin look like the bottom over which he is lying."

"Nothing new about that," interjected the intense assistant professor. "Bayliss had a picture of it in his classical textbook which has been out of print for thirty years, and dear old George Parker worked on the central mechanism for I don't know how long."

"Yes, but this fish is a bit different," Margot softly continued. "For one thing it's bigger, and the pattern it develops is more precisely like the background. I saw some of them, and it's really fantastic how they almost disappear in two or three minutes after they're put into a new aquarium with a different bottom. The big point is, though, that Mike is interested in how they recognize the pattern. All the older work is concerned with the motor side—what

makes the melanophores expand and contract and so on. Now that the computer boys have got some ideas about how pattern recognition might work, it struck Mike that it might be worthwhile to have a look at the sensory side again. Maybe he's right. Anyway I liked him and he seemed very sincere."

By this time lunch was almost over, and a couple of the technicians had begun to tidy up the place with the perfunctory help of two or three of the younger graduate students. Bill chatted for a few more minutes with Nick about what they would do next and left for his office where he knew that a number of people would be waiting to see him.

The first of these was a very promising graduate student named Marcus Hill. He was in his final year and seemed well on his way to completing an excellent thesis on the structure of certain biologically active compounds he had isolated from some wildflowers which he had found growing on his family farm in northern New York. He was very anxious to complete his analytical work by Christmas so that he could finish his thesis and get his degree by the end of the academic year. Today he had come in to discuss his most recent results and to ask Bill if he could have the full-time use of a recording spectrophotometer for the next three months.

As a matter of principle, Bill hated to assign expensive apparatus for the exclusive use of anyone below the rank of assistant professor, but this seemed like a special case. Marc was a very bright boy and a very decent human being who had made a place for himself in the group by his cheerful, cooperative attitude. None of the others were likely to kick very much if he were to enjoy a little special privilege toward the end of his time as a student. Finally, Bill was really touched by the eagerness with which Marc presented

his results and the shy but definite way in which he stated his needs.

In the end Bill contented himself with a few standard remarks about the importance of making the fullest possible use of expensive equipment and then said, "O.K., you've made a pretty good case. I think I may be able to find one for you somewhere in the department. I'll let you know in a couple of days."

After Marc had left with a more than usually cheerful smile and a warm "Thanks, chief," Bill picked up the phone and called Assistant Professor MacIntosh. "Hello, Mac. Just to save your valuable time, I'll not beat around the bush but come right out and ask if you are going to be using that Perkin Elmer recording I got for you this term? If not, I think I could find a home for it."

"Gee, chief, I've hardly unpacked the thing and got it working right, and now you want it back. What gives?"

"Well, just very temporarily, I thought that you must be spending most of your time on your lectures for the two new courses you're giving this term. Incidentally, Mac, you'd be surprised at the number of people who have stopped by to tell me how good those lectures are. The point is there's a very good boy in my group named Hill. Maybe you know him. He's got a very nice story on some plant alkaloids he wants to finish by the end of the year so he can take a job teaching in that new school in Nigeria in the fall. All he needs is about two months solid with a Perkin Elmer between now and Christmas, and he should have it all wrapped up. How about it?"

"Well, as a matter of fact, you're right about my spending a lot of time on those lectures," Mac replied, "and the day before yesterday, Jerry King called from Philadelphia to ask if I could write a chapter for him in his advanced textbook. Peter Vincent was going to do it until he accepted

the chairmanship of the President's panel on new frontiers in chemistry or whatever it is."

"Gee, Mac, that's quite an honor both for you and the department," said Bill with an honest note of admiration and pride in his voice. "I always knew you were good, but I didn't realize that others would think you are ready to step into Peter's shoes. Anyhow it's obvious you won't have any time for the lab until the new term begins. I'll tell Marc he can pick up your spectrophotometer this week."

"Hey, wait a minute," groaned Professor MacIntosh. "Maybe it's OK to let it go until Christmas, but I want some guarantee that it will be back in good working condition. I don't want to spend a couple of weeks cleaning it up and another month waiting for new parts."

"Put your mind at rest," replied Bill, relieved that the negotiation had gone off so easily. "I give you my word it will be back on January first in tip-top condition all ready to go. I'll even see that it has all the new accessories that have come out since it was delivered. Thanks a lot and good luck with the review."

With that Bill got up, lit a cigarette, and went out to tell Mrs. MacAvoy to call Marc and tell him he could pick up the Perkin Elmer. Two or three other students had relatively simple questions he could deal with while standing in front of Mrs. MacAvoy's desk, and one of the younger but very brilliant boys wanted him to just look at a crystallized enzyme he had just produced as the triumphant end of some six months' work. Bill was delighted to hold the bottle up to the light, to shake the bottle slightly to separate out a couple of the largest crystals for a better look, and to make the appropriate appreciative noises.

"Congratulations, Bob. You know well enough that I was afraid you had taken on too big a job for a starter. Now you've got it six months ahead of time. But I guess you

deserve it for dreaming up that novel precipitation procedure. Take an extra martini for me when you and Betty go out tonight."

Bill's office hours came to an end in a fairly long conference with Assistant Professor Sam Corbin who had just received an offer of an associate professorship at an excellent liberal arts college. Bill never looked forward to these discussions about the career decisions of his friends in the department. It was frightening to think that what a man decided today might determine the whole future course of his life, from whether or not he would do any worthwhile research to whether his wife would be happy or bored to death.

Like other sensible men, Bill had decided long ago never to give direct advice on occasions of this character. Nevertheless, he knew well enough that what he said about an individual's future in the department or his chances for getting the next professorship to fall open somewhere else would have a considerable bearing on what the individual decided to do.

It almost always turned out, though, that the people who came to him had pretty much made up their minds and merely wanted to see how their decision sounded to an older person whom they liked and respected. Often, also, the decision was only a half-conscious one, and talking about it made it clearer and more satisfactory.

Sam Corbin, a good-looking, reasonably extroverted sort of person in a tweed jacket, entered the office as he had hundreds of times before, sat down, and began to fill his pipe. "Well, Bill," he began, "I've just about decided to take that professorship at Niederlin. It's a good school, they've just got a big gift for a new chem lab, and they tell me I can have as much as one-half time in research. Incidentally, Gwen graduated there and would love to go back.

Also my kids are growing up, and Niederlin admits the children of faculty members for free and pays most of their tuition if they want to go to another small college. I'm not sure that mine wouldn't be better off in a somewhat smaller place than this Ph.D. factory we're in.

"The only thing that bothers me, of course, is the idea of leaving the big-time circuit. I know I'll be renouncing the possibility of contributing to research in a really distinguished way. Of course, there is plenty of competent work being done in the top thirty or forty of the country's liberal arts colleges, and Niederlin is one of the best. The fact of the matter is, though, that you are expected to spend a good deal more time teaching and participating in what the catalogue calls the 'life of the college,' than is true in a place like this."

Sam paused, and Bill recognized his cue. "Everyone knows, Sam, that these are the toughest decisions one has to make. But let's get one thing straight right away. You're welcome here as long as you want to stay. As you know, I've already asked the Dean for a tenure appointment for you, and it will come up at the next meeting of the regents. I don't see why there should be any difficulty. Everybody in the department likes you, and I would very much dislike losing you after our years together. On the other hand, I don't feel justified in urging you to stay against your better judgment. Old Stillman at Niederlin has only three or four more years to go as head of the department, and I should think you would have an excellent chance to succeed him.

"As a matter of fact," Bill muttered a little uncomfortably, "they said something to that effect when they talked to me last week."

"It's a little hard to predict what you'll get if you stay here. If I should leave, for example (and I certainly don't have any plans to do so), the board might well want to

look outside for some big name. They did recently in physics, and I have the impression that they are feeling their oats and are anxious to put the University on the national map, especially in science. It's beginning to dawn on some of the businessmen that academic research helps business, and they haven't overlooked the fact that a lot of defense money is going to the Northeast and to southern California because of MIT and Cal Tech.

"If they don't go outside, you'd have a chance to be chief, of course, but so would Al and Jerry and possibly even Jack, who recently made quite a splash at the Atlantic City meetings with his paper on hydrophobic bonding. I just can't predict how this cat might jump."

"Nice of you even to put me in that category, Bill. I know I'm only marginal when it comes to a university chairmanship anywhere. Actually, when I see how much time you have to spend going to committee meetings and suffering fools as gladly as you can, I'm not sure I want to be a chairman anyway. It really is more a matter of when does a research worker admit to himself that he isn't going to get the Nobel Prize. I know it sounds silly put that way. I never really have thought I had a chance for that specific recognition but, symbolically, I mean that probably all scientists pin their hopes for their self-justification on contributing something really important in the way of scientific discovery."

"I know what you mean, Sam," replied Bill, and somehow his voice sounded different from the way it had before. "Deep down I suppose all of us want to be known as the guy who thought up the modern equivalent of the ring structure of benzene, or the phase rule, or at least did something unprecedented like synthesizing urea."

"Yes, I guess most of us do," interrupted Sam, "but on

even a simpler level, we all seem to feel that there is something a little indecent about anything which isn't the pure pursuit of new knowledge. No one ever seems to take a different job without someone else muttering either that he 'saw the handwriting on the wall,' or 'really liked administration and committee meetings,' as if that was some sort of mental illness, or worst of all 'he just about had to because his wife likes nice things.' "

Bill thought a moment, and then rather slowly began to talk in a way which suggested that he was putting some thoughts together for the first time. "What it all comes down to, Sam, is that in order to do anything really well, you have to believe in it down to the tip of your toes. Frequently, though not always of course, the best painters, the best poets and writers, and notoriously the best opera singers and ballet dancers are difficult to live with because they feel compelled to sacrifice just about everything to the ultimate perfection of their art. Actually, the best scientists seem to have less need than the best artists to sacrifice 'everything' for their creative urge. Offhand, I can't think of any top scientist who was as absolutely nasty to his wife as Leo Tolstoy or as difficult for his boss to deal with as Michelangelo was for Pope Julian.

"Nevertheless, a research scientist is bound to think that research is the most important thing in the world. I think so myself for that matter.

"It's not the only thing though, and I wonder if some of those characters who are so vocal about not wanting to teach or do administration are really not protecting themselves from something. Basically, they just may not want to recognize that they aren't good with people. Many of them seem to be unable to tolerate situations where there isn't a clear yes or no answer as there usually is in a lab.

All things considered, administration and teaching seem to make more demands on what people call 'the whole man' than pure research does."

"Thanks for putting it that way, Bill, even if you don't believe it yourself. You're right in guessing that that's about where I've come out. Actually, I couldn't think of leaving science altogether. It's simply my life; the way I look at everything from planting my garden to the possibility of immortality is conditioned by my scientific training. If I never did another piece of research in my life, I would always think of myself as a member of the scientific community.

"I'll probably be writing their Dean in a week or so that I'll take the job. I'll finish out the year here, of course, so you'll have plenty of time to find a replacement. I will miss the gang here in the department, and most of all I'll miss you, Bill. Everything I am professionally and a good deal of what I am as a person I owe to you, and you know it."

Bill was touched enough to have difficulty in thinking of the right thing to say, so he merely put out his hand and said, "Thanks, Sam, we'll miss you just as much, and thanks too for letting me know so soon."

After Sam left, Bill had half an hour to transact routine departmental business with Mrs. MacAvoy before going off to the weekly interdepartmental seminar on coding and information. This was something of an experiment directed at bringing together people in the various departments concerned with modern information theory. Physics, chemistry, biology, mathematics, and linguistics were always well represented, and there was usually a sprinkling of curiosity seekers and communications theorists from sociology and psychology.

Today Bill was introducing the distinguished Japanese

biochemist, Tomomoto Yoshimo, who was going to speak on "chemical stabilizers in biological codes." Bill had worked in the same department with him some ten years before when Yoshimo had a traveling fellowship and had a very high regard for his industry and the originality of his approach to coding problems. He was also very fond of him as a human being, and he hoped the lecture would go well. He was a little afraid it wouldn't, partly because of the recondite nature of the subject and partly because of fears about the intelligibility of Yoshimo's speech. One could never be sure about the Japanese; all too often people who sound perfectly relaxed and easy to understand in their own labs become tense and virtually unintelligible in formal situations away from home. His anxieties proved groundless, however. Yoshimo had acquired a lot of confidence and skill in English since Bill and he had worked together, and he really had some fine work to talk about which helped to explain the extraordinary stability of genetic information over thousands, perhaps even millions of years. Although most of what he had to say was concerned with the nature of the chemical coding and was primarily of interest to the physicists, chemists, and biologists, there was also quite a bit about the significance of redundancy which served to enlist the interests of the linguists and mathematicians.

Afterward about ten of the group, together with their wives, came around to the Stones for cocktails and a buffet supper. Yoshimo, who had come to the United States at the special invitation of one of the big computer companies, had brought his wife. This evening she appeared in classic Japanese dress which elicited much interested comment from some of the other wives. The original impression of feudal conservatism was quickly dispelled when it turned out that Mrs. Yoshimo was actually a qualified psychiatrist

who had a lot of interesting things to say about different patterns of delinquency as seen in Japan and the United States when the subject came up after supper.

The evening went off very well although Jane and Bill exchanged wary glances when the social psychologist who had had one martini more than absolutely necessary insisted on offering a toast to the guests and making a short speech. Actually what he said was all true; and under the circumstances it went over better and seemed less sentimental than it might if reduced to cold print. The point he wanted to make was how nice it is that a distinguished professor from another culture could come halfway around the world and be perfectly understood as he discussed a subject which brought at least five different scientific specialities together in the same room. Such an event gave some reason to hope that the first half of the twentieth century, which had done so much to pull people and nations apart, might be followed by a time of greater mutual understanding and unity.

Since tomorrow was a working day, the party broke up about ten-thirty, and Bill and Jane had an hour or so together cleaning up and putting plates and glasses into the dishwasher before going to bed. This gave them each a chance to catch up with what the other had been doing and to exchange views on the people and the conversation of the evening.

As he filled Jane in on his talk with Sam Corbin, they fell to discussing the business of making decisions involving one's own future. One thing was clear to them both. You just can't be sure when you decide to choose this or that person for a spouse, and you can't be sure when you choose to be a research chemist instead of a chemical engineer. Actually, you won't be absolutely sure that you were right for a good many years after you've made the decisions. It

will be clear enough, of course, if you have been wrong, but how right can one be?

"You're getting too complicated for me, Bill; I'm going to bed with the thought that I couldn't have been righter when I selected a promising young scientist for my husband."

As Bill waited downstairs to catch the last ten minutes of "Modern Jazz for Modern Minds" (he played the clarinet in college and liked to keep up, at least in theory, with the Modern Jazz Quartet), he reflected that he probably hadn't made a mistake either—not about Jane and not about a career that provided so many days as full as the one just past.

12

Science and Art

ALTHOUGH SCIENTISTS OFTEN BECOME MORE COMPLETELY absorbed in their specialized careers than most people do, they also of course take part in all the other activities common to human beings. Their cultivation of the scientific attitude, however, frequently enables them to approach their other activities in unusual ways. In these three final chapters I would like to give a brief account of how a knowledge of science might condition one's attitude toward art and toward moral values, and finally how science is increasingly influencing decisions in regard to public policy. It would be a mistake to think that all scientists share all the views expressed. I am not even sure that a majority would share a majority of the views. I merely want to demonstrate in a very preliminary way that science does have something interesting to say about these important matters and that it is not simply an intellectual device for producing a higher standard of living in physical terms.

It is ordinarily believed that science has little to say about what are loosely called value problems. The overwhelming majority of nonscientists feel this way, and many scientists will be found to agree. Like most important questions in life, the problem of value has many sides. It is quite likely, therefore, that it will look very different depending on which

side we happen to be looking at. The very word "value" has many definitions and the mere discussion of these various meanings could fill several books this size.

When most people use the word "value" they are thinking in terms of whether or not a certain line of conduct is good or evil or a certain work of art is beautiful or ugly. In some cultures or in certain periods of history these two scales become very closely intertwined so that being good is thought of as being almost the same thing as being beautiful. In other cultures, like our own Puritan utilitarian one, goodness and beauty may draw rather far apart.

When we assert that science has little to say about value problems, we mean that the ordinary methods of science cannot help us to decide whether one picture is more beautiful than another or whether a given act is more honest than another. At a still deeper level, we mean that science cannot help us to understand justice or even to decide whether justice is a good thing or not. Strictly speaking, there seems little doubt about the reality of these limitations. On the other hand, I will try to show that science comes in contact with such value problems at many points, that awareness of values is indispensable for the progress of science itself, and that knowledge of science is indispensable for anyone who wishes to understand the problem of good and evil in the twentieth century.

But first let us explore a little further why it is that *strictly speaking* science has so little to do with value questions. The first reason appears, at least at first glance, to be purely technical; we simply haven't devised the right tools. We have good tools for measuring whether objects or phenomena are larger or smaller, heavier or lighter, faster or slower, hotter or colder, brighter or duller, greener or redder, louder or quieter, and higher or lower in pitch than are other objects or phenomena. But we have not devised

the tools for telling whether something is better or worse, or prettier or plainer than something else.

There are at least two advantages that are derived from the devising of tools to measure the qualities of objects. The first is that it enables us to agree about these qualities much more easily. The second is that we can describe the qualities in terms of numbers and thus enlist the powerful tool of mathematics in describing the relations between objects. It has already been pointed out that the business of ensuring agreement among all conscientious and informed observers is not merely a nice feature of science; it is one of the most important reasons for believing that science gives us something like a "true" picture of the world. Indeed, many thoughtful scientists who follow the philosophical school of thought known as Operationalism hold that the only way we can tell that a given experiment leads to valid knowledge and that any general proposition derived from it is true, is that we can describe the necessary operations in such a way that other people can carry them out and get the same results.

We are all so used to measuring things that we may overlook some of the more interesting features of the process. Notice, for example, that all the comparisons mentioned above as examples of measurements can be made at least fairly well by any natural or untrained man with his unaided senses. By merely looking at objects we can tell that some are larger than others, some are brighter and have different colors from others, and so on. To early man, all these attributes were thought of as qualities of the objects themselves. Some especially thoughtful man began to wonder, however, whether these qualities really were part of the objects or whether the sensations and perceptions produced in the observers weren't just as, or perhaps even more, dependent on the nature of the observer. One of the

most obvious things that led to this disturbing thought is the fact that different observers don't always agree even about the relative size of two different things. When we come to things like color and pitch, disagreement is even more common and more difficult to resolve. A color-blind person simply doesn't experience what the normal person sees as red. These discrepancies and many more like them gave rise over two thousand years ago to a long argument about the nature of knowledge and indeed about the very existence of the external world. We would be very foolish to go into this argument now, but some of you may want to read about it later on in courses in philosophy.

What concerns us here is that these discussions lead to a distinction between different ways of knowing which is quite useful in general discussions but should not be pushed very far toward its limits. This is the distinction between objective and subjective knowledge. To take a very simple case, if I tell you that the automobile standing by the curb is approximately 208 inches long, you either agree out of hand or, if you are a skeptic, you go out and measure it and get a figure which is satisfyingly close to mine. We agree to call the length of the car an objective fact. If, however, I say it is the most beautiful car on the road, you are not nearly so likely to agree, and if we are very good friends and are reasonably sophisticated in modern philosophy and psychology, I will admit that my view of the car is based on a subjective judgment and that this judgment is influenced by the fact that I own the car.

We are now in a position to reconsider our earlier statement that we have not yet developed suitable instruments for measuring values. The difficulty is more than technical. It is inherent in the fact that certain kinds of values are intrinsically more subjective in character than the properties we are accustomed to measure in the world of science. This

statement is particularly true of esthetic values. The feature that is most important about a picture or a piece of music is the way it makes you or me feel as an individual. I know, for example, that there are many people who feel that the choral bit in the last movement of Beethoven's Ninth Symphony is one of the greatest things ever written. It produces feelings about the joy and sublimity of life which are of the greatest importance to them. I don't happen to share these feelings, partly because I regard the music itself as overblown and partly because I can't get it out of my head that the Nazi party regarded it as a splendid expression of what it was trying to accomplish.

Naturally, I regret that I can't feel the way other people do about this music and about a number of other esthetic experiences, but it doesn't worry me terribly because I know that subjective responses to complex stimuli are extremely variable. It is therefore useless and possibly dangerous to look for a high degree of agreement in matters of esthetic value. It was the recognition of the subjective nature of value judgments in the esthetic sphere which prompted Cicero to make his famous remark that one should not argue about tastes. The fact that I do not respond favorably to the Choral Ninth should not (and of course it does not) affect the way other people feel about it. It has value for them, and my negative response substracts nothing from their positive one.

But if a substantial number of informed people refused to believe that the earth is round, we would feel pretty upset because we have come to believe that the truth of objective propositions does depend importantly on the degree of agreement among different observers.

If the methods of science cannot be used to determine questions of esthetic value, has science any concern with

art at all? I think it does. In the first place, both science and art are at base concerned with the same thing—the building up of some sort of shared picture of the world. The subjective nature of sensation and perception dooms all of us to what is ultimately a lonely existence, but science and art provide us with means for reducing the circle of loneliness which separates us from others. Science does it by reducing subjective sensations to measurable objective quantities. For example, it quickly got around the color-blind difficulty by pointing out that different objects reflect light of different wavelengths. It then devised instruments to measure both the wavelengths and the intensity of the reflected color. All sorts of what we loosely refer to as elementary sensations have been similarly reduced to pointer readings in a way that greatly increases the range and accuracy of our individual observations and facilitates the sharing of such observations with others.

The great theories of science extend this process of sharing to a much more profound level. In other words, they enable us to share not only the details of observations but complete pictures of how the details are put together. For example, all reasonably well informed people now share the same picture of the solar system and think of life as a constantly evolving pyramid with man as one of its more interesting products.

As we have seen, there are other parts of experience which have proved extremely resistant to reduction to numbers on a scale. Artistic creation may be looked upon as a method for breaking into the circles of subjective loneliness without reducing subjective qualities to objective quantities. Though it is less successful than science in developing general agreement, it has the enormous advantage of maintaining and deepening the individual's direct awareness of

life. It is our feelings rather than our thoughts that make life important to us and even determine whether we live or die.

Because the subject is so important, perhaps I ought to take a little time to explain what I mean by art as a means of sharing the subjective world. What the artist is trying to do is to devise ways of making other people feel the way he does about certain matters that are important to him. Much art enriches our lives by enabling us to see or hear more than we otherwise would and to share with the artist his joy in seeing the first flowers of spring or his admiration for deeds of heroism. More complex reactions with more practical objectives may also be produced. Many of Dickens' novels were only a very slightly camouflaged attempt to make the British upper class feel what it was like to be a little boy growing up in England during the Industrial Revolution. The very greatest artists, people like Shakespeare, Dostoevski, Michelangelo, and Bach, are primarily concerned with getting other people to share their feelings about what is currently referred to as the "human condition"—the tragic discrepancy between man's aspirations and his capacities, the conflict between individual liberty and the sense of divine order, the ambiguities which arise as sons love their mothers and become jealous of their fathers, the "last infirmity" which overcomes noble minds as a normal striving for excellence turns into "vaulting ambition." Since we are all doomed to suffer from these conflicts and ambiguities, it is the artist's business to share with the rest of us his view that irony and tragedy have at least a certain grandeur and may be part of a great design.

Not only are science and art both interested in enlarging the area of shared experience. At the higher creative levels, their techniques for doing so are closer than one might suspect. People who are not scientists often feel

that scientists are purely concerned with collecting facts and that scientific generalizations emerge automatically when enough facts have been collected. Indeed, Sir Francis Bacon, who had a good deal to do with getting the modern scientific era started, viewed science in this way. Since he was a very persuasive writer (and lawyer), his views have carried a good deal of weight. It is now clear, however, that scientific concepts and generalizations do not arise of themselves. They are acts of the scientist's imagination which bring order and coherence to what was before a meaningless or awkward collection of facts. In the same way, a work of art is a creation which produces order in the realm of subjective experience.

As Alfred North Whitehead said, "Art is the imposing of a pattern on experience, and our esthetic enjoyment in recognition of the pattern." [1] But science proceeds in exactly the same way and, as we have seen, the esthetic enjoyment produced by a new scientific idea is frequently one of the major reasons for preferring it to other less beautiful hypotheses.

The close relationship between scientific and artistic creativity has recently been eloquently set forth by J. Bronowski in a little book [2] that is so interesting and so easy to read that it relieves us of the necessity for further discussion here.

Notes

[1] *Dialogues of Alfred North Whitehead,* Boston, Little, Brown, p. 228, 1954.

[2] J. Bronowski, *Science and Human Values,* New York, Harper, 1959.

13

Science and Morals

THE RELATIONSHIP BETWEEN SCIENCE AND MORAL OR ethical values has a character somewhat different from the relationship between science and art and is even less well understood. Until very recently it was fashionable to maintain that science has nothing to do with deciding whether something is good or bad. Science is only concerned with what is, so ran the argument, not with what ought to be. Nonscientists supported this view because it helped them keep control of the really important things of life and because they feared the growing power of science and wanted to keep it in its place. Scientists supported the view partly because they were, in fact, more interested in things as they are and didn't want to get involved in the difficult business of deciding how they ought to be, partly because they wanted to be polite, and partly because it is very difficult to see how the scientific method can be used to decide moral and ethical questions.

We are still very much in the dark in regard to the latter point, but we are beginning to see that neither the scientist nor nonscientist can ignore the relationship between science and morals. Three points about this relationship are particularly clear. In the first place, science has greatly eroded the authority and prestige of the traditional custodians of moral values; secondly, science has enormously increased

the power in the hands of men; and third, science provides us with a much clearer view of the probable consequences of our acts than we have ever had before.

We shall discuss each of these questions separately. The tendency of science to erode traditional authority has been recognized for a very long time, and we shall mention it only very briefly. A full treatment of the historical aspects of the problem will be found in Andrew White's two-volume work, *History of the Warfare of Science with Theology in Christendom*. The point is that, up until recent times, organized religion took responsibility for explaining all aspects of the universe and for ordering men's relationship both to each other and with the divine order. The Bible in effect contained all the knowledge available at the time it was written on both science and morals. Indeed, science and religion were pretty much one and the same thing. As time went on in the Western world, the scientific knowledge and some of the moral insights of the Greeks and Romans were integrated into the system of Christianity by the brilliant intellects of the church fathers—especially perhaps St. Augustine and St. Thomas.

I speak here of the Christian religion because it is the most important to us and because it has had to make the greatest effort to integrate scentific knowledge into its structure. Many other religions have tended, of course, to take responsibility for explaining the natural world as well as for conducting the moral order.

It is painfully obvious that the progress of science since about the sixteenth century has given us an entirely different picture both of the universe and of the nature of man than that available to the Jewish prophets and Greek philosophers who produced the Western religions. The question thus arises, if religion was so wrong about the creation of the world, the motions of the heavenly bodies,

and man's relation to the lower animals, how do we know that it is right about morals and ethics. In point of fact, the Church itself thought of this question before anyone else and tried very hard to halt the progress of science, sometimes by argument and persuasion and sometimes by trials for heresy followed by execution. Even today, it is still illegal to teach the theory of evolution in at least one of the United States.

Surprisingly enough, religion has really lost little of its authority in the realm of morals and ethics, even though its prestige as an explainer of the natural world has been greatly reduced. Fears that men would give up honoring their fathers and mothers or go about murdering, stealing, and coveting when they found out that the Church was wrong about the speed of falling bodies have proved to be largely unfounded.

Science and religion have learned to live together, in large part because of the good will shown by both sides. In the first place, very few scientists really wanted to attack religion as such; most of them have been basically religious themselves, and even when they were not, they have usually believed that the existing moral order is as good as any available. The evidence seems to be that scientists have less tendency to steal, to murder, and to have multiple wives than does the usual run of mankind. What we have experienced during the twentieth century is a kind of truce between science and religion in which it is more or less agreed that science is free to deal with the material world and religion with the spiritual and that morals are to be regarded as part of the latter.

But this hands-off policy has been more and more difficult for the scientist to maintain. The increasing power of science has forced the scientist to consider the long-term effects of science on the conditions of human life. Decisions

about the use of power involve moral issues. Since scientists are ordinarily the first people to grasp the meaning of a new kind or dimension of power, they cannot escape a share in the responsibility for its use. Many of the physicists who worked on the atomic bomb both in England and the United States were at least vaguely uneasy about making it possible to murder tens of thousands of people in one blow, but it remained for the greatest of them to come right out and say that in some sense the physicists of this period have known sin. We are far from having digested that statement and have hardly begun to explore its implications. But it does, I think, mark the end of the time when science could regard itself as completely detached from the moral concerns of man.

It is by no means only in physics that increases in power heighten the sense of moral responsibility. Progress in biology and medicine now places upon men decisions which used to be left comfortably in the hands of God or to the impersonal forces of nature. Up until very recently, many babies born with grave physical defects did not survive, and many old people who had declined to the state of mere vegetables contracted pneumonia and died peacefully. Now it is possible for a large proportion of them to be kept alive by the use of antibiotics, blood transfusions, artificial kidneys, and so on.

The public has been made aware of the ethical problem through newspaper accounts of certain dramatic cases of euthanasia, but the basic situation is much deeper and more pervasive than these accounts suggest. The fact is that most people who die in their beds could be kept alive for at least a few hours, days, or even months if medicine always did all it knows how to do. There comes a time, however, when the advantages of keeping an unconscious, grossly deteriorated individual alive must be weighed

against the disadvantages—the cost in money, in doctors' and nurses' time, and above all in the emotional strain of fighting a long-drawn-out battle with death. In a few years it will be literally true that at least the time at which most people die will be determined by a doctor or by a group of people including doctors, who will decide not to do something they know how to do.

At the other end of the life span, science is slowly but steadily providing the background for decisions in regard to how many and what kind of children will be born. In all civilized countries parents use scientific knowledge to determine the size of their families, and increasingly the question of the overall size of national populations is becoming a matter of public discussion. Clearly many "value problems," both esthetic and moral, are involved in such discussions, but science is intimately involved in them also.

Although knowledge of human genetics is still in its infancy, there is already enough to be taken into serious account in decisions about family planning. Some nations have already employed genetic ideas very crudely in laws aimed at preventing criminals and other defectives from having children. On an individual basis, parents increasingly consult physicians and geneticists about the chance of having defective children when the parents are known to carry defects of one sort or another. In certain very clear cases, the defects are so serious and the genetic evidence so compelling that the decision is relatively simple. In other cases, the genetic evidence can only be expressed as a not very large probability and the danger of having a child with a relatively mild defect must be weighed against many other factors which constitute important values to the prospective parents and to society. In practice, it is very difficult for the doctor or the geneticist not to get involved with these value problems, however much he

would like to remain a bloodless and objective scientist.

Science is also increasing our control of people's feelings and behavior in a way that raises very significant value problems. Tranquilizers and analgesics are generally welcomed for their power to reduce the sense of fear or pain. Other compounds may reduce aggressive behavior; still others may increase it. In extreme cases, no serious moral problem seems to be involved in the prescription of such drugs. Giving a tranquilizer to a person who is paralyzed by fear or anxiety so that he can function in society is obviously a good thing to do. On the other hand, fear is a normal part of everyone's makeup and serves to protect us from dangerous situations. It is not easy to decide when normal useful fear ends and abnormal anxiety begins. It is even true that many artists and other creative people have been driven by what were clearly abnormal anxieties to produce work of the greatest importance. At the present time tranquilizers are being advertised as a means of avoiding stage fright, a perfectly normal experience which almost everyone has had, and which in reasonable amounts is probably necessary for the best performance onstage. Furthermore, learning how to control and direct such normal fears is probably a desirable part of growing up. How does the physician or the patient himself weigh these complicated value questions when deciding to give or take a drug? Can scientists who have made such decisions possible entirely escape responsibility for thinking about them?

We have now arrived at our third point. Science enables us to foresee the consequences of our acts. By doing so it can frequently contribute to questions involving moral values by laying out the probable results of alternative actions so clearly that the final choice becomes a mere matter of common sense. In most cases the results of a scientific analysis will agree very well with traditional moral

values. Science puts a very high value on truth and honesty, for example, if only because science itself is impossible unless scientists are truthful with one another. For much the same reasons science places a high value on the welfare of the community as a whole and it therefore supports all the traditional injunctions against disrupting community life by killing, stealing, committing adultery, and so on. Indeed the results of scientific investigation emphasize the unity of mankind all over the world; racial and national differences seem very small to the scientist when he compares them with the large number of traits all men have in common. As we have seen in an earlier chapter, science itself is a highly international activity and scientists tend to think in terms of the world community more often than most people do. This fact, together with the scientists' acute consciousness of the destructive effects of modern weapons, tends to make some scientists support proposals for "world government" or at least greater international control of armaments. This activity has led to accusations from time to time that scientists may be less patriotic than other people. This is not true except in the sense that their patriotism is likely to extend to a larger community than one based solely on national values.

The results of scientific investigation of the consequences of the seven deadly sins provide convincing evidence of the value of traditional moral attitudes regarding individual behaviors. The undesirable effects of gluttony, for example, can be specified in terms of increased tendency to illness, lowered efficiency, and early death. The scientist who records the tortured physiology of the drug addict or the pathologist who observes the shrunken liver of the drunken bum is just as convinced about the evils of drink as the nineteenth century minister who mounted the pulpit to preach hellfire to the victims of these evils.

Two principal differences distinguish the scientist's approach to moral values from traditional attitudes. In the first place, he has more difficulty in being sure that something is either absolutely good or absolutely bad. In the second place, he is beginning to discover and define moral problems that nobody ever thought of before, or at best thought of only very casually.

The scientist's difficulty in being absolutely sure about values stems in part from his general difficulty in being sure about anything. As Alfred North Whitehead has said, "There are no whole truths; all truths are half-truths. It is trying to treat them as whole truths that plays the devil." [1] We have already seen that sad experience has taught the scientist that the accumulation of new evidence may upset his most strongly held views on the nature of things. An even greater difficulty comes from his observation that the value of things varies with circumstances. This so-called relativity of knowledge is characteristic even of basic physics, but a few biological examples may be easier to understand. At the very simplest level we may consider a species of animals which has developed a heavy coat of hair or fur. Such animals are well adapted to life in cold climates but do rather badly in the tropics. In value terms, hair may be defined as good in one place but bad in another. We now know that the value of certain human traits varies in the same way with environment. A particularly interesting example, which has been thoroughly studied from the medical, genetic, and chemical points of view, is a disease known as sickle cell anemia. This is a genetic disorder which results in the production of hemoglobin of a slightly abnormal composition. Children who inherit the disorder from one parent have a very slight tendency to develop anemia but are much less likely than normal people to develop severe malaria. People who inherit the controlling genes from

both parents become severely ill with anemia and usually die before becoming adults. In parts of the world which are free of severe malaria infection, the sickle cell gene is wholly "bad" so far as we can see. In malarious areas, however, one gene is "good" but two together are bad.

The same principle of judging the value of qualities or functions in terms of the surrounding circumstances can be carried to higher levels involving issues which are more obviously in the moral sphere. Careful anthropological study has shown, for example, that marriage patterns and sexual customs vary widely from place to place and from time to time. In many parts of Asia it is still true, as it was in the Western world until recently, that marriages are arranged by parents with relatively little reference to the wishes of the partners. We tend to regard this as an unjustified interference with personal liberty, but there is much evidence that under certain circumstances the method works very well. Even more drastic difference in marriage patterns are of course well known. In some societies one man may have several wives and in others one wife may have several husbands. In the Western world such departures are looked upon as crimes. Scientists are for the most part prepared to agree that under our conditions monogamy is the best pattern and that it is immoral to depart from it. But most scientists who worry about the matter at all would find difficulty in asserting that other patterns are bad in an absolute or universal sense.

A particularly interesting and currently very important example of the bearing of science on moral values is found in what is currently known as the population problem. Virtually all societies have set a very high value on marrying and having children. Sterility has been regarded as at best a great misfortune and often as a punishment for some obscure fault or sin. In many societies the failure of a

wife to bear children is a cause for divorce. In the Western world, the Biblical injunction to go forth and multiply became incorporated in what we have referred to as the Natural Law of the Church derived from Aristotle's habit of describing nature in terms of its intentions or purposes. The doctrine in this case runs more or less as follows: the obvious purpose of the reproductive instinct is reproduction, the use of this instinct without intending to have children is therefore unnatural (that is, sinful). This view was universally held in the Western world until very recent times. At present it is identified primarily with the Roman Catholic Church, although orthodox Communists reach the same conclusions through a somewhat different process of reasoning.

Science has become involved in two ways in the reappraisal of what might be called the moral value of having children. In the first place, the application of scientific knowledge to agriculture, to industry, and to public health has made it possible for many more children to live to adulthood than used to be the case. In the second place, science has used its analytical abilities to demonstrate that a declining death rate and constant birth rate are sure to result in a rapid increase in population. Along with this increase will come increasing pressure on natural resources, increased contamination of the water we drink and the air we breathe, social and political unrest, and numerous other troubles incompatible with the good society we are struggling to achieve.

The scientist is quite ready to agree that many of the factors in this discussion involve questions of value which science is not prepared to resolve as such. For example, as a human being, the scientist may prefer a world which has forests and swamps where he can go and be alone on weekends, but he cannot use his science to demonstrate

that this is a better sort of world than one which is completely filled with people all living in multistoried buildings and eating synthetic food. He feels very strongly, however, that science should be listened to as it tries to describe what the world will be like if birth rates remain high while death rates continue to drop. Once he is convinced that people understand what the issues are, he should be content to let society decide the value questions involved. But he cannot agree that devotion to a traditional moral value excuses modern men from considering the facts. He finds it particularly difficult to decide value questions on the basis of Aristotle's or anybody else's views as to what nature intends. As we found in Chapter 2, the idea of intent or final cause has proved very unhelpful in understanding the movements of falling bodies and the dynamics of the solar system, and there seems little hope that it will be any better in understanding the reproductive instinct.

Finally, we come to what may be the most surprising aspect of the relationship between science and moral values. Far from being uninterested in and detached from such matters, science has called attention to the need for enlarging the scope of morals. In a sense, science has invented new sins to worry about. It turns out that, for a considerable period of time, people have been doing a number of things that contribute to the discomfort and sometimes to the death of other people without being very clearly aware of it. The growth of modern statistical methods has made it possible to describe the results of such acts with considerable accuracy.

Professor C. H. Waddington, writing as early as 1941, put the matter in this way: "The adoption of methods of thought which are commonplaces in science would bring before the bar of ethical judgment whole groups of phenomena which do not appear there now. For instance,

our ethical notions are fundamentally based on a system of individual responsibility for individual acts. The principle of statistical correlation between two sets of events, although accepted in scientific practice, is not usually felt to be ethically completely valid. If a man hits a baby on the head with a hammer, we prosecute him for cruelty or murder; but if he sells dirty milk and the infant sickness or death rate goes up, we merely fine him for contravening the health laws. And the ethical point is taken even less seriously when the responsibility, as well as the results of the crime, falls on a statistical assemblage. The whole community of England and Wales kills 8,000 babies a year by failing to bring its infant mortality rate down to the level reached by Oslo as early as 1931, which would be perfectly feasible; but few people seem to think this a crime."[2]

Since he wrote these paragraphs, it has become more and more obvious that we must begin to think of such statistical responsibilities in much the same way as we have thought in the past about individual crimes. The people who die because of the pollution of the air or the reckless driving of an automobile are just as dead as if an individual had run a sword through them. Those responsible for polluting the air or driving the car improperly are just as responsible for the deaths as if they had committed an old-fashioned crime. The only difference is that they didn't know in advance the names of the particular people who were going to die.

Sooner or later, it will seem very odd that we bear down hard on a man who lures a child into a car and later strangles it in a park, while we shower high salaries and other dignities on advertising managers and TV artists who lure thousands of teenagers into the statistically fatal habit of cigarette smoking.

The questions raised in this chapter are obviously very complicated and far-reaching. I have no intention of coming to any conclusion about them. All I hope is that enough has been said to discourage the commonly held idea that science has nothing to do with values. Though science is not a method for deciding value questions, it clearly bears on them at many points. By its skill in defining questions and predicting the results of alternate courses of action, science can certainly suggest answers, even though it cannot by itself decide between alternatives.

Notes

[1] *Dialogues of Alfred North Whitehead,* Boston, Little, Brown, p. 16, 1954.

[2] C. H. Waddington, *The Scientific Attitude,* Harmondsworth, Middlesex, Penguin Books Ltd., p. 31, 1948.

14

Science and Policy

How does the individual scientist become involved with value problems in practice? In the first place, like any citizen, he is likely to take part in discussions of public policy which depend on the weighing of scientific evidence. Many communities have recently had very active debates on whether or not to fluoridize water supplies. In these discussions scientific evidence on the reduction of dental caries and the possible hazards to be expected when various concentrations of fluorine are added to drinking water comes into conflict with certain somewhat mystical values surrounding the concept of purity and more concretely with the freedom of parents to decide for themselves whether their children should have cavities or not. Although there may be a good deal of sound and fury in such discussions, in the long run they lead to a clearer understanding of the objective issues and perhaps to a better appreciation of some of the subjective values involved.

In recent years, scientists have increasingly found themselves writing about both the practical hardware and the moral questions concerned with the testing and use of the atomic bomb. Some of these essays appear in specialist journals like the *Bulletin of the Atomic Scientists,* but others are published in magazines of wide popular circula-

tion. Many of these contributions reveal the inexperience of scientists in dealing with questions of broad public policy, but the overall result must certainly be that the public has a much clearer idea of what is at stake in an all-out atomic war than it would have had if all our scientists had resolved that they had no concern for the way science is used.

Much of the confusion of such discussions arises naturally out of our real ignorance of some of the most important effects of atomic bombs. Similar difficulties are likely to arise whenever a relatively new bit of science is offered in the world of practical affairs. Whenever a new technique is introduced, somebody has to make the judgment that its probable advantages outweigh its probable disadvantages. But we can never get an entirely clear idea of the advantages and disadvantages until after the technique has been in use for some time. The difficulty of arriving at completely satisfactory judgments in such matters is seen very clearly in the introduction of new drugs and vaccines. Efforts are always made to reduce the risk by carrying out tests on animals, but finally there comes the time when someone must decide to see what the new procedure does to people. This kind of situation gives an opportunity for two rather different sorts of discussion. The first and easiest is a purely scientific debate as to what the risk probably is. This is carried on in terms of the number of animals used, the kinds of tests employed, and so on. There is more room for disagreement here than the nonscientist might imagine. A good example may be found in the introduction of the Salk vaccine at a time when there was a sharp disagreement about the probability that some batches might contain live virus. The argument involved several technical issues too complicated for discussion here. The point is that there can be, and in fact usually are, serious differ-

ences of opinion on purely scientific matters when new procedures are introduced into practice. The reason is that one wants to enjoy the benefits of the new procedure as soon as possible. If one waited for complete agreement on the exact probabilities, one might have to wait many years.

Even when we have a clear picture of the mathematical probabilities, our troubles are not over, for now we encounter a value problem in addition to the purely scientific problem discussed above. Let us say, for example, that there is a disease that kills one person out of a thousand, and we have in our hands a vaccine which we are pretty sure confers immunity on 95 percent of the people we give it to. Other things being equal, it should reduce the mortality rate from one in 1,000 to one in 20,000. But unfortunately we know that the vaccine may itself produce a fatal case of the disease in one out of 10,000 people. It appears that if we give our vaccine to a million people we will save 950 people who would otherwise have died from the disease and bring about the deaths of 100 other people who might not have died, leaving us with a net gain of 850. In objective, cold-blooded terms, it looks like a good trade, but the fact of the matter is we don't do it. The decision grows out of the way we settle the value question. In its crudest terms it appears that it is morally and ethically preferable to allow 900 people to die by doing nothing than to contribute to the deaths of 100 people by doing something. Most of us instinctively agree with this assessment and it has the sanction of Hippocrates' ancient instruction, "In the first place, do no harm."

Nevertheless, we do not push the conclusion to its absolute limit. Again, most people instinctively agree that there comes a point at which the odds convince us that the risk is worth taking. For example, we regularly urge every-

one to be vaccinated against smallpox even though we know that perhaps as many as one in a million will contract a dangerous encephalitis. There is no formula that can be used to decide just what the odds should be in any particular case. In practice, a committee of experts will weigh many different factors before coming to a conclusion. The decisions of such committees provide excellent examples of the close working relationship between science and values which is increasingly characteristic of modern society.

In the Soviet Union, something over half of the top policy-making positions in the government are occupied by persons with scientific or engineering educations. The situation in the United States is far different, but even so, scientists here have become policy makers to an extent that would have been regarded incredible thirty years ago. Their most obvious role is in making the policy of science itself. Science has become very big business indeed, with an estimated 15 billion dollars spent on research and development in 1961–1962. The wise expenditure of such sums as this requires much careful thought and detailed planning—much of it necessarily by scientifically trained executives. The scientist administrator is thus becoming a familiar figure not only in such obviously scientific organizations as the National Science Foundation and the Bureau of Standards, but in almost every government department and throughout industry as well. Even the State Department has a scientific staff to advise on science as it affects international relations. For the past ten years a prominent part of the White House organization has been the Office of the President's Science Advisor, supported by a group of full-time assistants and a part-time committee of civilian scientists. Originally formed to give advice on the use of science in national defense, the office now is involved in a

much broader range of policy making—the handling of drug addiction, the technical and diplomatic conflicts of importing beef from countries with hoof-and-mouth disease, planning for increased use of automation in the keeping of hospital records, how to improve the teaching of social science in high school—to name but a few.

All these activities require a nice blending of the methods and attitudes of science with the value judgments, practical wisdom, and political institutions characteristic of the man of affairs. On the whole, the scientists seem to have taken to their increasing responsibilities surprisingly well, and it seems highly probable that the influence of science on high policy will continue to increase.